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Technical Report

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NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California 93043

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March 1972

CONSTRUCTION ASSISTANCE VEHICLE (CAV)—

The Design, Fabrication, and Technical Evaluation of an Experimental Underwater Vehicle

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CONSTRUCTION ASSISTANCE VEHICLE (CAV)—The Design, Fabrication, and Technical Evaluation of an Experimental Underwater Vehicle

Technical Report R-762

YF 38.535.003.01.004

by

S. A. Black and LT R. E. Elliott

ABSTRACT

An experimental diver-operated Construction Assistance Vehicle (CAV) was designed, fabricated, and evaluated in order to determine the feasibility of and general specifications for a prototype diver work vehicle. The CAV, fabricated from off-the-shel components, is capable of carrying 1,300 pounds of wet weight cargo between the surface and the ocean bottom work site. The craft's pneumatic and hydraulic power is available to operate hand-held power tools. Over 100 test dives were conducted in the ocean, with the craft being operated to a maximum depth of 110 feet. Operational testing proved the CAV to be a safe and effective means for delivering cargo and for powering diver tools. Also, when the CAV was compared to other vehicles, it was determined that the CAV is the only system that provides the working diver with total ocean bottom support. The necessary refinements are delineated, and general specifications for a prototype vehicle are presented.

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Construction assistance vehicle						
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INTRODUCTION

Under the sponsorship of the Naval Facilities Engineering Command (NAVFAC), the Naval Civil Engineering Laboratory (NCEL) is developing tool systems for use by naval underwater construction forces. Considerable research has been directed towards providing safe and reliable underwater tools and power sources. Both pneumatic and hydraulic tool systems have been investigated.* The objective of the NAVFAC/NCEL program is to provide working divers with tool systems which are compatible with the hostile environment and which will increase their working capabilities.

In conjunction with the tool systems, the Laboratory has developed an experimental Construction Assistance Vehicle (CAV) which can provide working divers with an underwater "pickup truck" capable of short-haul transportation of tools, power supplies, equipment and personnel between the surface and the underwater construction site. This report describes the design, fabrication, and technical evaluation of the experimental CAV.

BACKGROUND

The CAV represents the completion of the first step in the development of a work vehicle for use by the naval construction divers. This experimental vehicle was designed as a test bed by which criteria and general specifications for a prototype fleet vehicle could be established.

The concept for the CAV was formulated in 1966, and a project was established to design, fabricate, and evaluate a material-handling unit for underwater work systems, such as diver tools and power sources, cargo-handling equipment, manipulators, and excavating equipment. The techniques and equipment generated from the material-handling unit are to be used in the development of future continental shelf work vehicles, either diver operated, remote controlled, or operated from a manned, one-atmosphere capsule. Figure 1 shows a simplified conceptual drawing of the proposed material-handling unit.

* Naval Civil Engineering Laboratory. Technical Report R-729: Technical evaluation of diver-held power tools, by S. A. Black and F. E. Barrett. Port Hueneme, Calif., Jun 1971. (AD 726161)

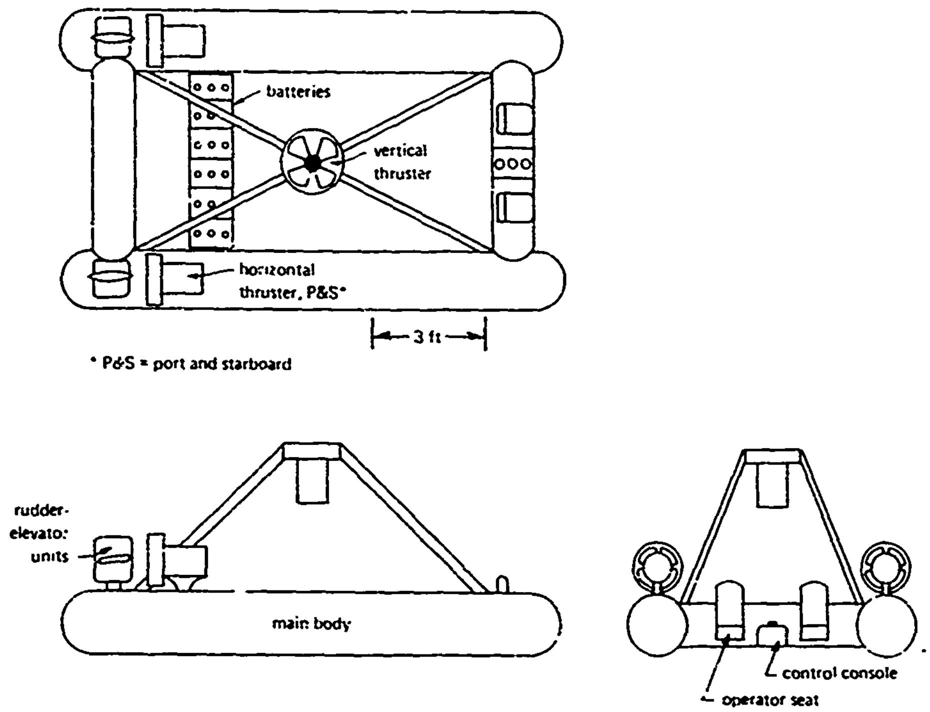


Figure 1. Conceptual drawing of material-handling unit.

The material-handling unit concept was carried through a preliminary design during FY-68. Final design, complete with fabrication drawings, was accomplished during FY-69 by a naval architectural firm under contract to NCEL. The vehicle, named the CAV, was fabricated by a marine hardware firm during FY-70. Modification, test, and evaluation of the CAV was accomplished during FY-71/72 at the Naval Civil Engineering Laboratory.

The preliminary design for the CAV, Figure 2, established that the vehicle should have the following general specifications:

Cargo bed	4 feet x 7 feet
Cargo capacity	2,000 pounds (wet)
Endurance	4 hours
Collapse depth	250 feet
Operational depth	120 feet
Operational personnel	2 divers
Speed (submerged)	3 knots
Power	Electro-hydraulic

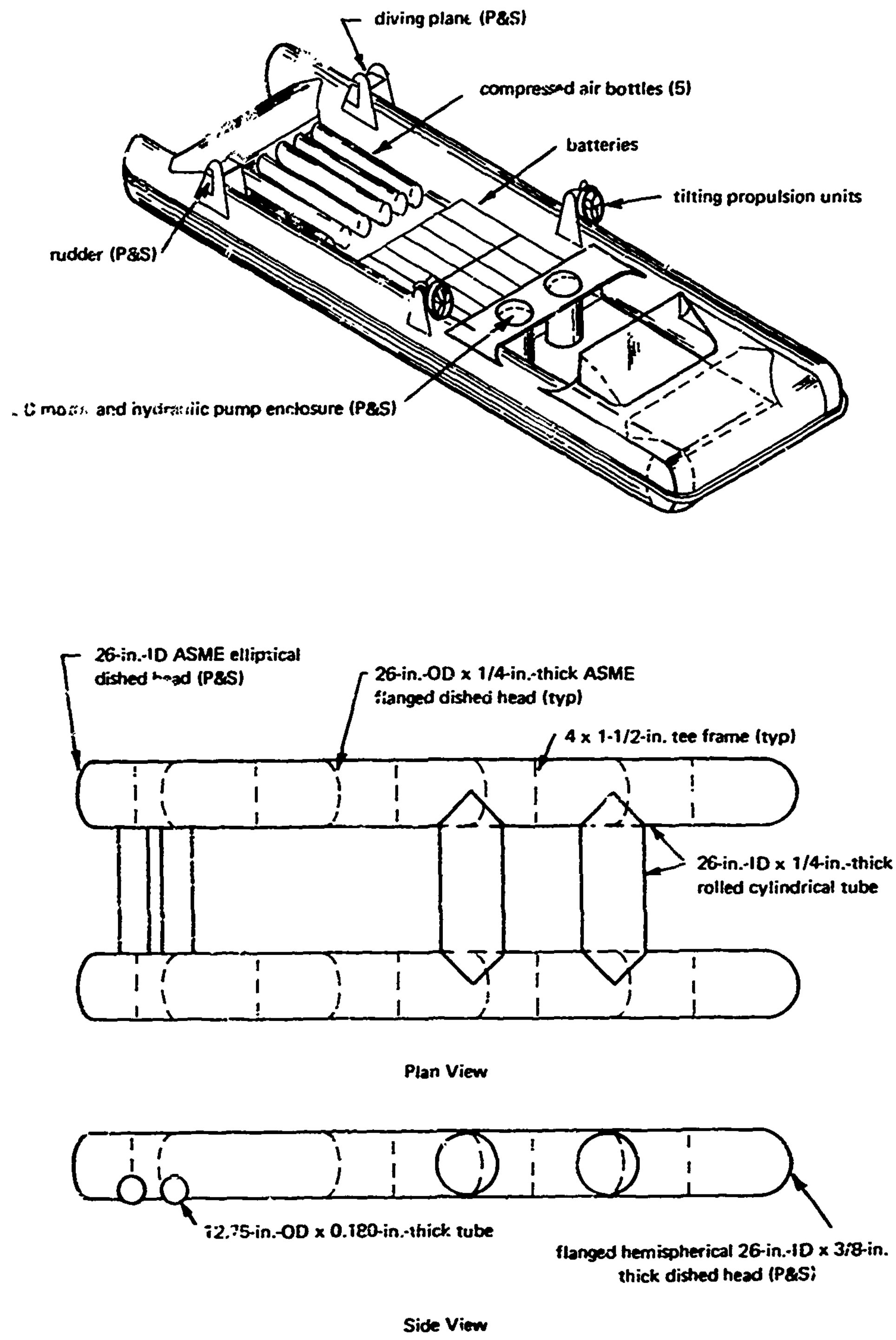


Figure 2. Preliminary design of CAV.

In order to minimize costs, maximum use of "off-the-shelf" components and standard fabrication techniques was specified. Design constraints based on cost, simplicity, reliability, and safety included: (1) use lead–acid batteries; (2) utilize an electro-hydraulic propulsion system that could also power hydraulic tools; (3) eliminate electrical control and circuitry in vicinity of diver–operators; (4) utilize mechanical linkages for actuation of all control functions; and (5) provide an easily accessible cargo area.

Figure 3 shows the first configuration developed from the above specifications. The craft was to be 25 feet long, 9 feet wide, and consist of two longitudinal 30-inch-diameter tubes and transverse fore and aft tubes. The craft was to be electro-hydraulically powered, and the rudders, planes, and tilting propulsion units were to be mechanically actuated. The transverse tubes were to be used for fore and aft water ballast trim.

Analysis of the configuration indicated that it had insufficient stability when submerged. Thus, it was necessary that a fixed ballast be added at a greater distance below the tubular hull structure. The addition of ballast required an enlarged skeg. The skeg structure was used to form a ballast tank, thus enabling the main hull to be reduced in diameter. In addition, the fixed ballast was made movable to accommodate fore and aft trim.

During the latter period of the design, a plywood mockup of the CAV cockpit was fabricated, complete with instrumentation and controls. This mockup was used to determine the best location for the vehicle controls and to establish basic operational and safety procedures. (A mockup is considered to be the single most important design aid for developing a safe and operable vehicle.) The mockup also provided an excellent tool for training the CAV operators. A more complete discussion of the mockup and its use is contained in the Appendix.

DESCRIPTION OF VEHICLE

The catamaran-hulled vehicle (Figures 4 and 5) was fabricated primarily from mild steel. The main hull tubes provide most of the vehicle's buoyancy for submerged operation. The two tanks (main ballast tanks), located below the main hull structure, provide buoyancy for surface handling of the vehicle. Two auxiliary ballast tanks, integral to the main hull structure and centered at the cargo deck, provide a variable seawater ballast capability to compensate for cargo weight.

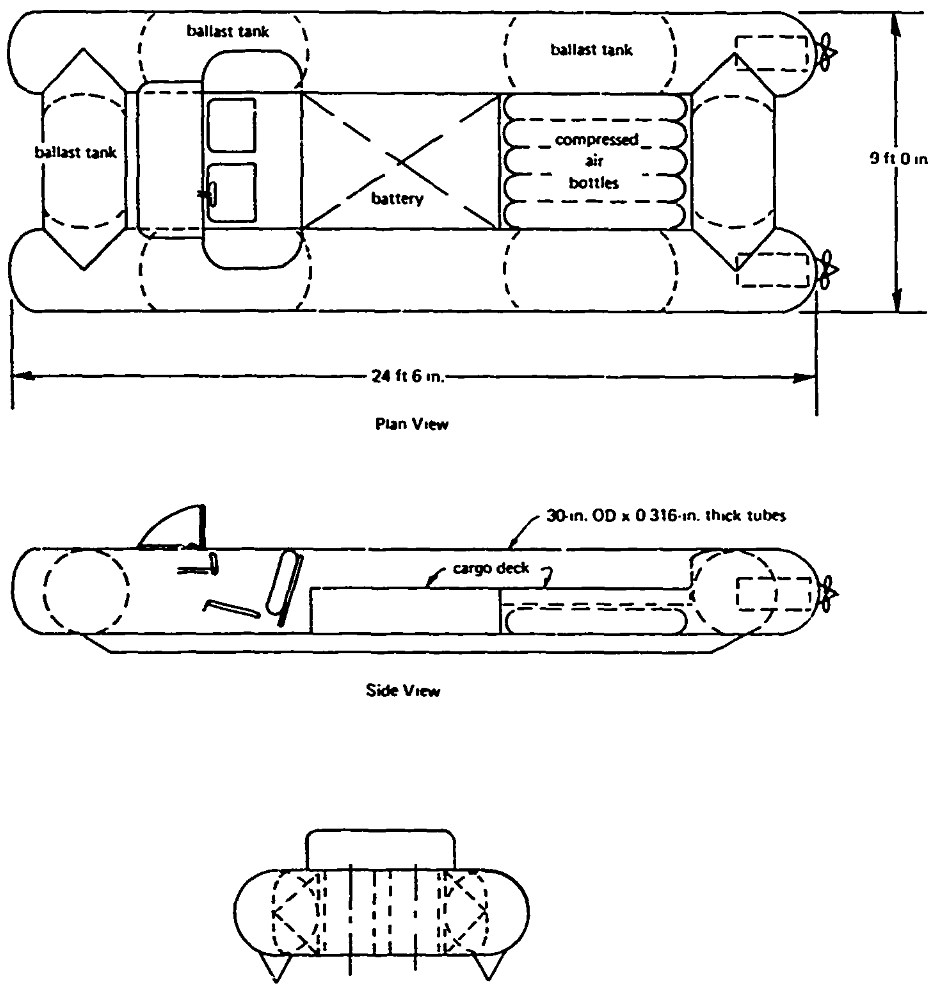


Figure 3. First configuration developed by design agent.

The primary power to operate the vehicle's propellers and pumps is supplied by two sets of oil-filled, pressure-compensated lead–acid batteries. Each battery powers a 60-volt-DC constant speed motor. The electric motors are coupled to variable-volume oil hydraulic pumps. Each motor pump unit is housed in a nitrogen-filled, pressure-compensated container.

Two pairs of hydraulic motors coupled directly to propellers provide thrust for operating the vehicle. The upper propellers (main propulsion units) rotate through 190 degrees to provide variable thrust direction for submerged

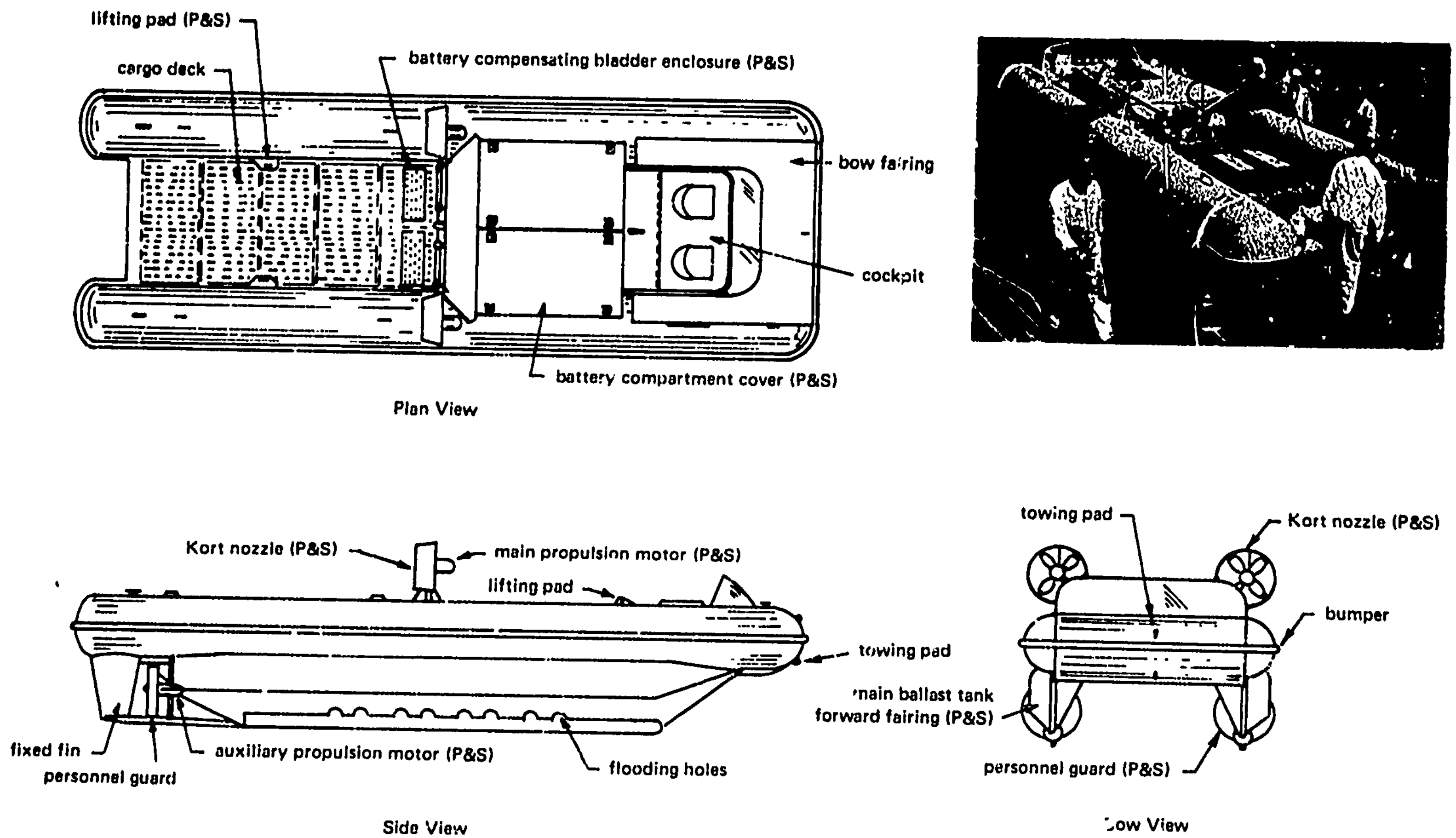


Figure 4. General external configuration of the CAV.

operation. The lower propellers (auxiliary propulsion units) provide thrust for surface handling of the vehicle. Two hydraulic motors are also coupled to seawater pumps to enable the vehicle operators to adjust the amount of water in the auxiliary ballast tanks.

Two 300-pound trim weight assemblies are located in the lower part of the main ballast tanks. The fore and aft adjustment of the trim is powered by a pneumatic motor located in the cockpit. Compressed air, which is used to operate the trim weights, to provide life support, and to blow the main ballast tanks, is supplied by five 220-ft^3 high-pressure bottles located under the cargo deck grating. The craft's pneumatic and hydraulic power is available for operating hand-held power tools.

All controls in the electro-hydraulically powered craft are actuated mechanically from the cockpit by the diver–operator; there are no electrical controls in the cockpit vicinity. The craft contains no movable planes or rudders; steering is accomplished by independently varying the speed of the port propeller and starboard propeller. Fore and aft trim is corrected by moving the vehicle's trim weights. Vertical thrust for diving is accomplished by rotating the main propulsion units. Table 1 lists the major vehicle components with a brief description of each. The major vehicle characteristics are:

Overall length	26.5 feet
Overall width	9.5 feet
Overall height	7 feet
Weight	18,630 pounds
Cargo bed dimensions	11 x 4.5 x 1.5 feet
Maximum operating depth	120 feet
Maximum submerged speed	2.5 knots
Maximum surface speed	2.8 knots
Endurance at maximum speed	4 hours
Battery power available at 70°F, 60 volts, 95 amps	37 kw-hr
Compressed air	1,100 ft^3
Cargo capacity	1,300 pounds
Maximum fore and aft trim capability	2,800 ft-lb
Trim rate	140 ft-lb/sec
Hydraulic power available for tools	6 gpm at 1,400 psi

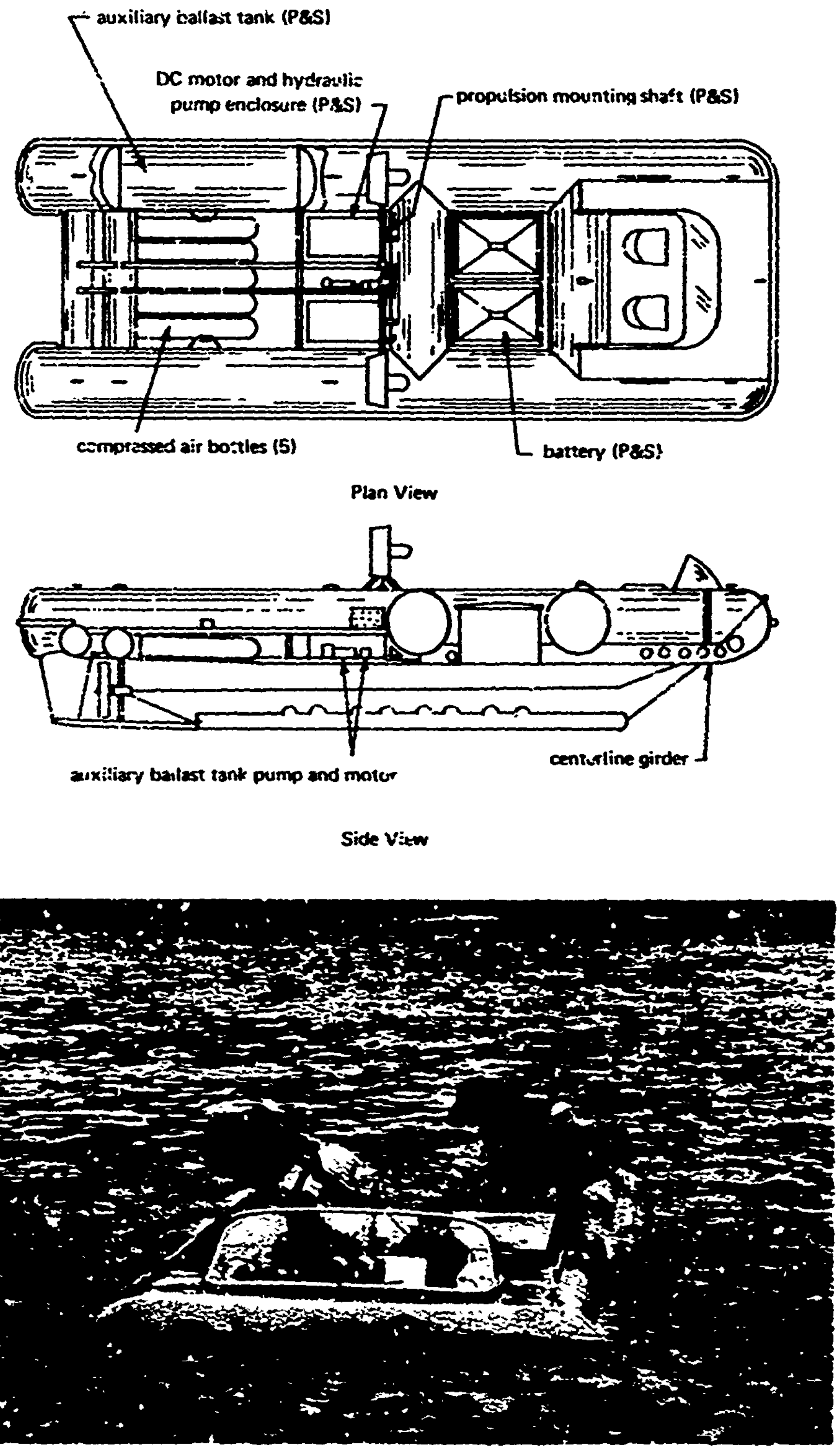


Figure 5. General internal configuration of the CAV.

Table 1. Major Vehicle Components

System	Major Component	Quantity	Function	Description	Control
Electrical	Battery	2	Primary power storage	Lead–acid, 60 v, 18.5 kw-hr at 98 amp and 70^{o}F. Approximately 2 x 3 x 3 ft and weighs 2,500 lb dry; oil-filled and pressure-compensated	Directly connected to switch via electrical cables and dry connectors
	Electric motor	2	Provides driving force for hydraulic pumps	6-hp, compound-wound, DC motors; 60 v, 95 amp, 1,850 rpm	Mechanical circuit breaker in motor/pump containers with mechanical linkage to cockpit
	Circuit breaker	2	For turning on and off electric motors and for circuit overload protection	100 amp working with 150 amp overload protection	Mechanical linkage; shaft penetrators to push-pull cable to lever in cockpit
	Cable and connector	4	Provides electrical connection between battery containers and electric motor/pump containers	Submersible (dry connectable) connectors molded to single conductor cables (100 amp)	Mechanical make and break connection which must be done on surface
	Charging leads	4	For charging batteries with CAV in or out of water	20-ft electrical leads with dummy plugs	Remove dummy plug and connect to battery charger leads
Hydraulic (oil)	Pump	2	Provides oil flow and pressure to propellers, ballast pumps, and diver tools	Axial piston, lever operated, variable volume, reversible 6 gpm at 1,200 psi, 1,850 rpm	Mechanical linkage; shaft penetrators to push-pull cable to lever in cockpit
	Main and auxiliary propulsion motor	4	Converts hydraulic energy to mechanical to turn main or auxiliary propellers	Variable speed, reversible motors, rated 6 gpm at 1,200 psi, 429 rpm	By direction and flow/pressure from hydraulic pumps

continued

Table 1 Continued

System	Major Component	Quantity	Function	Description	Control
Hydraulic (oil) (cont)	Ballast pump motor	2	Converts hydraulic energy to mechanical for powering seawater ballast pump	Reversible gear motor; rated 2.5 gpm at 1,200 psi, 1,500 rpm	By direction and flow/pressure from starboard hydraulic pump
	Pump	2	Pumps seawater to, from, or between auxiliary ballast tanks	Hydraulically driven, variable volume; rated 0-15 gpm at 75 psi over ambient	Selection of valves and levers in cockpit
	Water ballast magnitude indicator (cockpit)	2	Provides operator with direct read out (in cockpit) of amount of seawater in each auxiliary ballast tank	0-15-psi pressure gages recalibrated to read in pounds of seawater. Introducing seawater into closed tanks increases pressure in tanks, etc.	Bleed valves at tanks for calibrating gages
	Water ballast magnitude indicator (on ballast tanks)	2	Provides direct read out of amount of water in each auxiliary ballast tank	Sight gages enable diver to visually determine water level in each ballast tank	Not applicable
Trim weight	Movable weight	2	Provides trimming moments to correct for various loading conditions and provides pitch control while underway submerged	310-lb (dry) lead weight assemblies mounted on rubber wheels in order to roll weights fore and aft in 8-in.-diam pipe tubes skegs	Mechanical-pulley, cable, drum, gear connection to air motor
	Air motor	1	Provides driving force to move trim weights fore and aft in tubes skegs	1.1-hp reversible air motor; rated 260 rpm, 44 cfm at 90 psi	Operator moves handle on air motor (in cockpit) fore to move weights fore and aft to move weights aft
	Trim weight indicator	1	Provides operator in cockpit with indication of the longitudinal position of trim weights	Vertical pointer display	Mechanical, screw gear to push-pull cable to pointer

continued

Table 1. Continued

System	Major Component	Quantity	Function	Description	Control
Main propulsion unit thrust direction control	*Mechanical linkage*	1	Articulates thrust direction through 190° to enable CAV to produce vertical and horizontal thrust for submerged control	Main propulsion units can be directed so that thrust is straight up to straight down through the arc where the thrust is aft	Mechanical; worm gear, shaft, universal joints, right angle gear, handwheel actuated
	Lock	1	Locks main propulsion units in a specific thrust angle	Manual release	Gear lock is actuated via push-pull cable and T-handle in cockpit
	Indicator	1	Provides operator with indication of main thrust direction	Vertical pointer display	Mechanical; rack and pinion to push-pull to pointer
Cargo bed	*Cargo deck*	1	Provides space to carry and lash down cargo	Approximately 11 x 4.5 x 1.5-ft cargo storage area above steel grating	Not applicable
	Davit socket	2	For mounting davits to load/unload cargo if required	4-in. sockets at the aft and on each side of the cargo deck	None
Operator seats	–	2	Provides adjustable diver support and restraint for scuba-outfitted diver-operator and buddy	Fiberglass/PVC structure with scuba bottle support, adjustable longitudinally and vertically	Manual adjustment of pinned support frame
Propulsion units	*Propeller guard*	8	Prevents divers from inadvertently getting extremities in propeller screws	Aluminum grating	None
Pressure compensation	Regulator	1	Provides pressure-compensating nitrogen gas to the motor/pump containers, propulsion unit housings, and hydraulic accumulator in order to maintain an overpressure (to prevent seawater leaks)	Standard double-hose, two-stage, scuba regulator modified to maintain output pressure at 2 psi above ambient	Automatic

continued

Table 1. Continued

System	Major Component	Quantity	Function	Description	Control
Pressure compensation (cont)	Pop-off valve	2	Exhausts compensating gas from system to prevent excessive overpressure	1/2-in. pop-off valves set at 4 psi above ambient	Automatic
	Gage	1	Monitors pressure in compensating gas storage bottle	Standard diver submersible pressure gage	None
Main propulsion units	Kort nozzle	2	Primarily improves screw efficiency, and secondarily acts as screw shield	Cast aluminum, airfoil-shaped nozzle	Adjustment bolts for centering around propeller
	Propeller	2	Changes hydraulic pump rotary output into thrust	24-in. diam, 15-in. pitch, 4-bladed aluminum propeller clipped to 20 in. for close clearance with Kort nozzles	None
Auxiliary propulsion units	Propeller	2	Changes hydraulic pump rotary output into thrust	20-in. diam, 15-in. pitch, 4-bladed aluminum propeller	None
Water screen	–	1	Protects operator and assistant from hydrodynamic forces	Standard small boat wind shield	None
Attitude indicator	–	1	Provides operator with pitch and roll angle	Integrated "ball-in-curved-tube" displayed with $\pm 6^{\circ}$ and $\pm 60^{\circ}$ scales in pitch and roll	Adjustment screws in mounting bracket
Emergency buoy	–	1	Indicates CAV location in the event of an emergency exit of the vehicle	Dumbbell-shaped float with tether line wrapped around center	Pull D-ring on float bracket

Main Hull Structure

Figures 4 and 5 show the general configuration of the catamaran-hulled vehicle. The main hull structure consists of two 26-inch-ID cylindrical tubes that run the length of the craft and four transverse tubes that tie the hull together. Most of the submerged buoyancy is provided by these tubes, which were designed for a collapse depth of 250 feet.

The longitudinal tubes are fabricated from 1/4-inch-thick mild steel (ASTM A-6) rolled plate. The hull design provides for a 1/32-inch corrosion allowance and an out-of-roundness of 3/16 inch. The forward ends of the longitudinal tubes are closed with hemispherical heads and the aft ends with dished heads. The hemispherical heads improve the hydrodynamic shape of the bow.

The longitudinal tubes are subdivided by 26-inch-OD flanged dished heads. Ring stiffeners are provided midway between each dished head to further stiffen the hull tubes. The forward transverse tubes are constructed similarly to the longitudinal tubes; the diameter of the aft transverse tubes was made smaller to provide access to the cargo deck for loading and unloading.

Main Ballast Tanks

The primary function of the main ballast tanks is to provide buoyancy for surface handling of the vehicle. In addition, the tank structure functions as a landing skeg and as a support for the trim weight system. The tanks, which are soft ballast tanks (that is, the bottoms are permanently open), are completely flooded when the vehicle is submerged.

The tank side plating is 1/8-inch-thick mild steel (ASTM A-7). There are five equally spaced web frames and watertight bulkheads at each end. The upper boundary of the tanks is formed by the main hull longitudinal tubes. The lower boundary of the tanks is an 8-inch-diameter standard steel pipe, which houses the trim weights.

Support Structures

The cargo deck structure consists essentially of two longitudinal trusses and a transverse truss. Deck gratings are provided as a means for securing cargo. Battery supports are provided between the two larger transverse tubes, and battery covers reduce the hydrodynamic drag of the vehicle.

The bow structure supports the sheet metal fairings as well as protects the divers in the event of a collision. Sheet metal fairings under the cargo deck reduce hydrodynamic drag.

A transparent water shield installed at the forward end of the cockpit protects the divers from water impinging directly upon them.

Auxiliary Ballast System

The auxiliary ballast system (Figure 6) provides a means for adjusting buoyancy of the vehicle to compensate for cargo. In addition, the system is used for correcting port and starboard trim of the vehicle. The 6-foot-long tanks are an integral part of the main hull longitudinal tubes and are located approximately abeam of the center of the cargo deck. With no cargo on the vehicle, the tanks are designed to carry approximately 2,000 pounds of seawater (approximately 3/4 full).

The fill and transfer system for the auxiliary ballast tank compensates for loads removed or added to the vehicle; this is essentially a hard ballast system. Water is pumped to and from the sea and between the tanks by a hydraulically driven water pump.

Manifold valves for selecting the direction of water flow are located in the cockpit within easy reach of the diver—operator. Pressure gages, calibrated in pounds of seawater, are located in the cockpit. Since this is a closed-ballast system, pressure in the tanks varies as a function of the amount of water in the tanks (that is, if the tanks are empty, then the gages are at atmospheric pressure or zero pounds of water). In addition, site gages are located on the outboard side of the tanks for monitoring the amount of water in the tanks. To change the water ballast, the operator selects the correct flow path via the manifold valves and activates the water pump. Provision is also made for blowing water from the tanks with the vehicle's compressed air system.

Compressed Air System

A schematic of the vehicle's compressed air system is shown in Figure 7. The air system supplies air for blowing and venting the main ballast tanks, for blowing the auxiliary ballast tanks, and for maintaining diver life support. The system powers a pneumatic motor for operating the trim weights. In addition, the compressed air can be used for powering the pneumatic tools. The five 220-ft^3 high-pressure bottles are located below the cargo deck grating.

Electro-Hydraulic Power System

The CAV utilizes an electro-hydraulic system to provide the driving force for a number of the vehicle's dynamic components. In this system, electrical energy is converted to fluid power (oil under pressure), then converted to mechanical power to drive the vessel's propellers and pumps. The efficiency of the system is approximately 30%; the estimated efficiency of each component is shown in Figure 8.

Figure 9 shows a simplified diagram of the power systems in the vehicle. The port and starboard systems are independent; provision has been made for cross connecting the hydraulic systems in the event of a failure in either system.

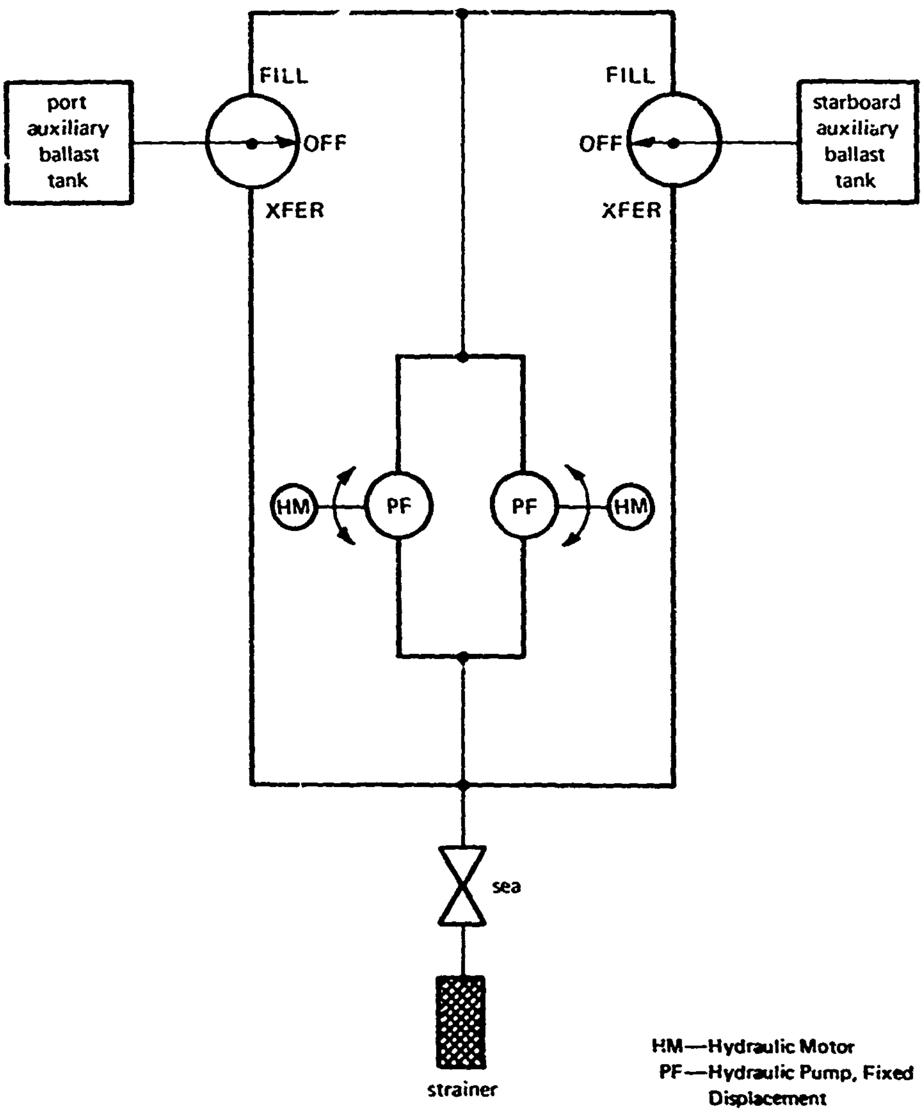


Figure 6. Schematic of auxiliary ballast system.

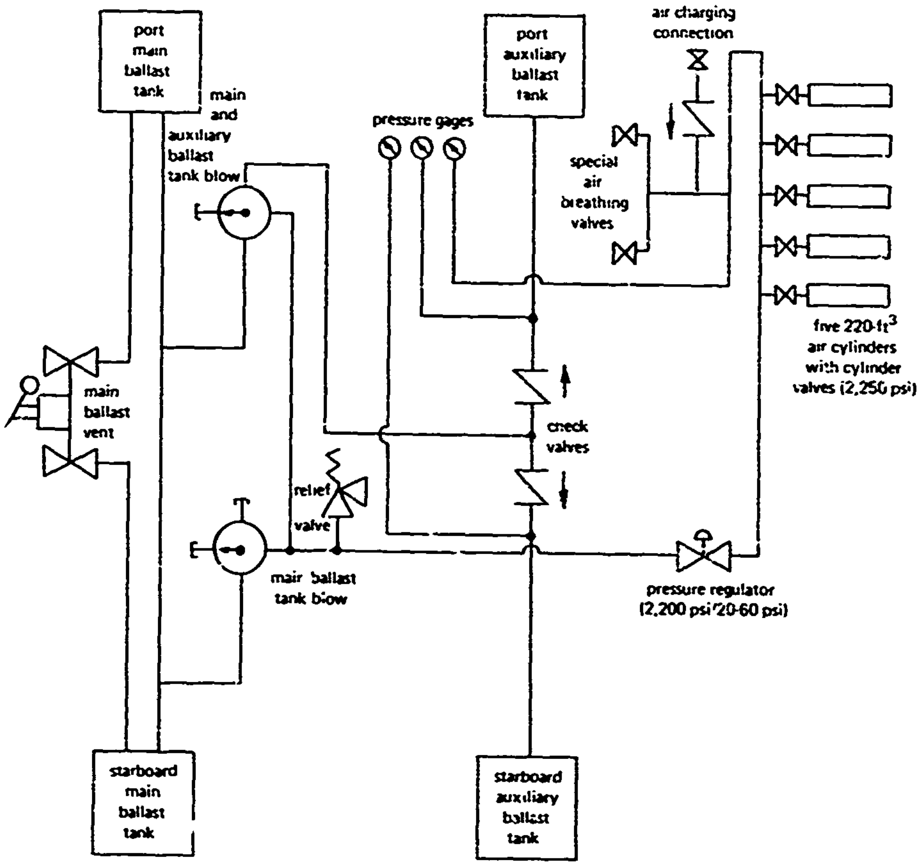


Figure 7. Schematic of compressed air system.

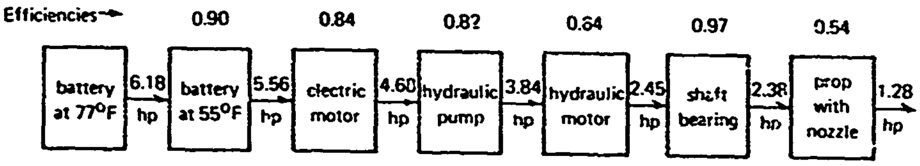


Figure 8. The efficiency and horsepower available through each component in the electro-hydraulic power system.

The primary source of power consists of two independent 30-cell, oil-filled, pressure-compensated, lead–acid batteries (Figure 10). Each battery pack provides 60 VDC, 18.5 kw-hr at 77°F based on a 4-hour discharge rate. The battery containers, fabricated from a 1/8-inch-thick aluminum plate, are equipped with venting connections and relief valves for eliminating hydrogen from the containers. Pressure compensation is accomplished with an oil-filled bladder exposed to ambient pressure.

Two 60-volt, 6-hp, 1,850-rpm, 100-amp, compound-wound DC motors are directly connected to the hydraulic pumps and are housed in separate, dry, pressure-compensated containers (Figure 11). An electrical circuit breaker is housed in each container. Connection between the battery boxes and the motor pump containers is made via electrical cables equipped with dry underwater connectors.

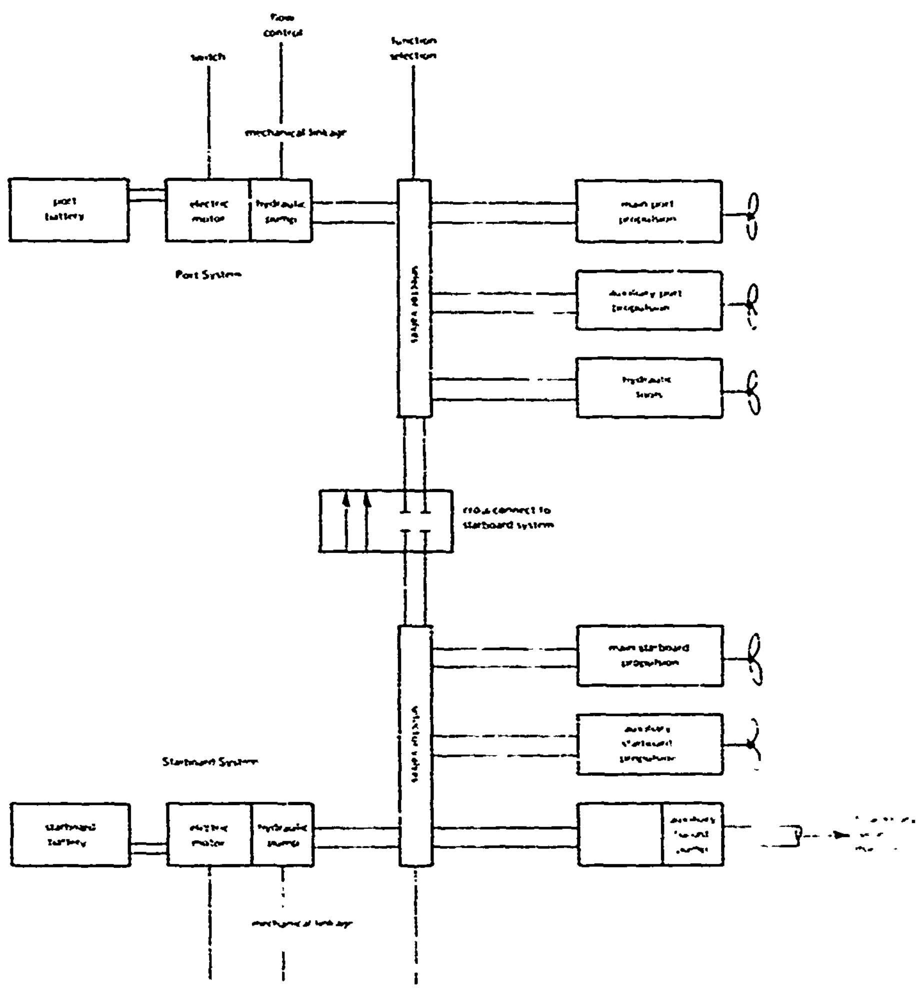


Figure 9. Block diagram of CAV power train.

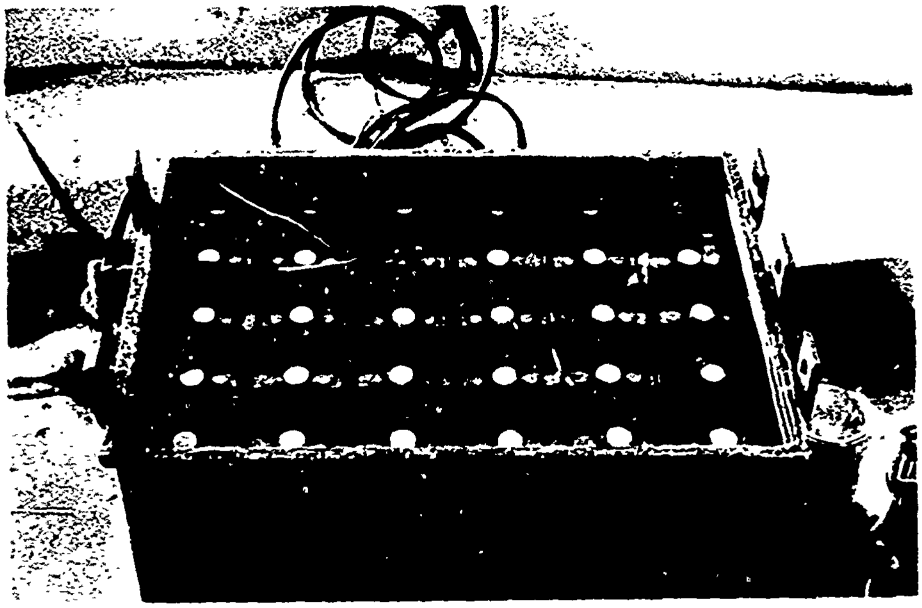
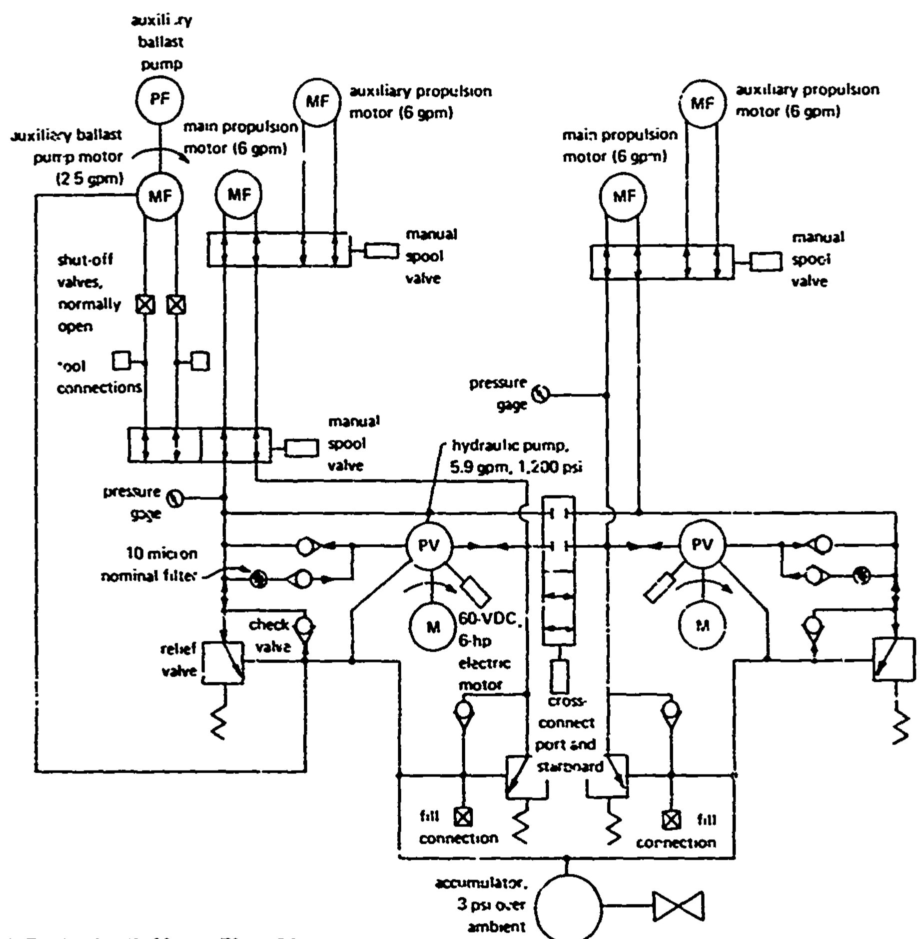


Figure 10. One of the CAV battery packs with cover removed; note individual cells.

Figure 11. CAV electric motor, hydraulic pump, and pump-motor container.

Figure 12 shows a schematic of the hydraulic system. Oil flow is generated by the pumps, which are directly coupled to the electric motors. The pumps are variable volume, axial piston with manual controls and are rated at 6 gpm at 1,200 psi. Flow control is achieved by manually adjusting the piston displacement by means of a movable swash plate. The four propulsion motors are reversible and of the positive-displacement gear type. Each motor has a rating of 6 gpm at 1,200 psi, 429 rpm and delivers approximately 2.4 hp to each propeller. The ballast pump motors are internal gear, 2.5 gpm at 1,200 psi, positive-displacement types.



MF—Hydraulic Motor, Fixed Displacement
PF—Hydraulic Pump, Fixed Displacement
PU—Hydraulic Pump, Variable Displacement
M—Electric Motor

Figure 12. Schematic of CAV hydraulic system

The hydraulic system is reversible. Two pressure reducing valves isolate the low-pressure side of the system regardless of flow direction. The accumulator serves as a pressure reservoir that maintains fluid in the systems to compensate for leakage and pressure variations.

Pressure Compensation System

The CAV hydraulic system was pressure-compensated in order to preclude seawater intrusion. A pressure of from 2 to 4 psi above ambient is maintained in the low pressure portion of the hydraulic system, the motor/pump containers, and the propulsion motor housings.

The compensation system (Figure 13) is a simple regulator—relief valve arrangement. A standard 71.2-ft^3 scuba bottle, located on the starboard side of the cockpit, supplies nitrogen to a modified double hose scuba regulator. The regulator supplies sufficient nitrogen to the compensated areas to maintain at least a 2-psi overpressure. The two pop-off relief valves open when the internal pressure exceeds ambient by 4 psi. To avoid possible explosion from arcing electric motors and switches in an atmosphere with a high oxygen partial pressure, nitrogen was used as the pressure-compensating gas.

Mechanical Systems

Mechanical linkage (Figure 14) and gear boxes enable the operators to rotate the main propulsion motors through a 190-degree arc; thus the operator can adjust the thrust direction of the units, thereby controlling ascent and descent of the vehicle. The main propulsion motors are inclined at a 30-degree angle to keep the prop wash from impinging on the main hull structure and, at the same time, to keep the Kort nozzles within the beam dimension in order to minimize damage to other structures.

The main propulsion motors are housed in pressure-compensated containers mounted on the outboard end of the inclined, rotating support shafts. They drive counter-rotating, 20-inch-diameter, 15-inch-pitch propellers (clipped from 24 inches) mounted in cast aluminum Kort nozzles.

The auxiliary propulsion motors are similar to the main propulsion motors, except that they do not swivel. Since the auxiliary propulsion system was designed for surface use, vertical thrust was not required. Propeller guards protect the divers.

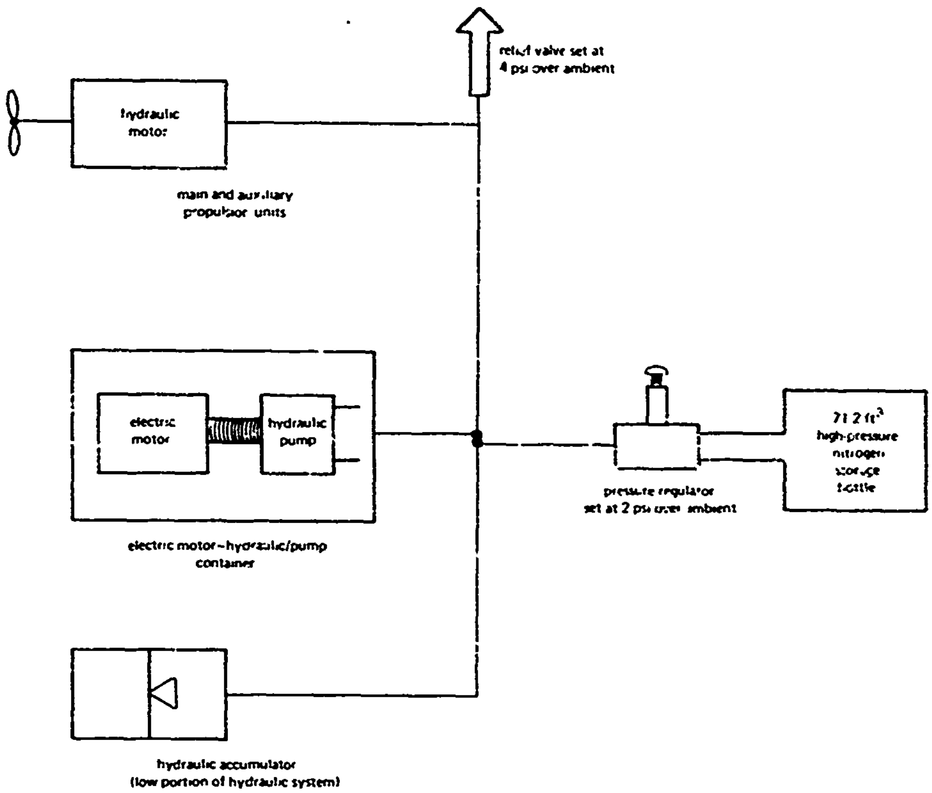


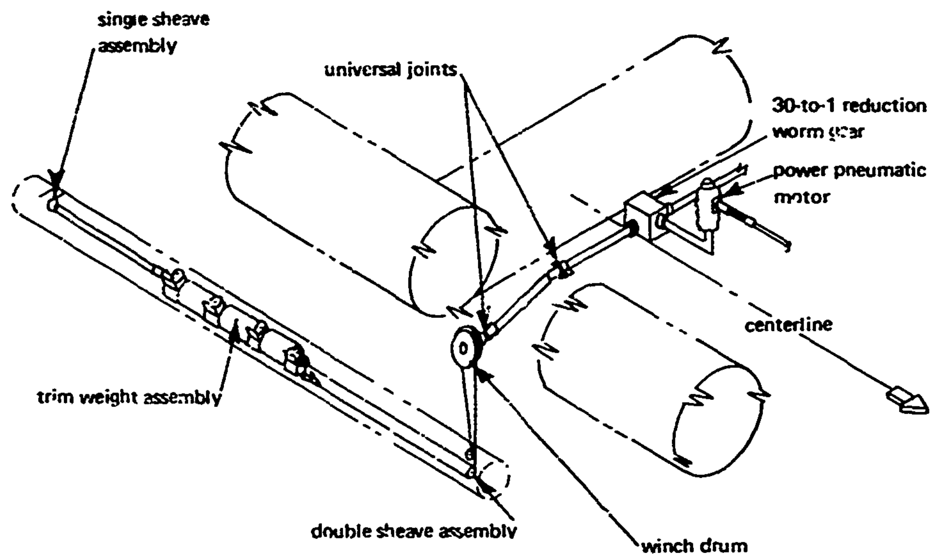
Figure 13. Schematic of pressure compensation system.

Fore and aft trim correction is accomplished by moving two 300-pound weight assemblies that are housed inside an 8-inch-diameter steel pipe located at the bottom of the main ballast tanks. Mechanical linkages connect the assemblies to the cockpit. The diver–operator controls the position of the weights with a reversible pneumatic drill motor. A cockpit indicator shows the operator the relative position of the assemblies.

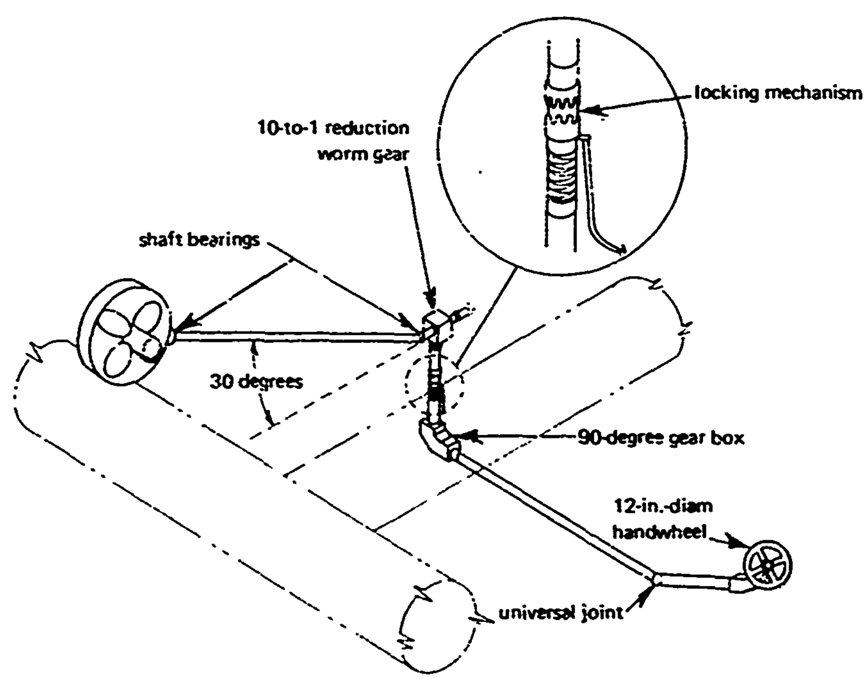
Each trim weight assembly (Figure 15) consists of three 7-inch-long, 6-inch-diameter, lead-filled pipes and four 3-wheeled caster units. The assemblies can be moved from 5 feet forward to 5 feet aft of the vehicle's center of gravity.

Control and Instrumentation Arrangement

The controls and instrumentation, shown in Figure 16, have been placed in easy reach and view of the diver–operator. The position and configuration of each control and instrument was determined from an



Trim Weight Linkage



Main Propulsion Rotating Linkage

Figure 14. Arrangement of mechanical linkages.

extensive human factors study. Operational controls consist of: (1) port and starboard electric motor control switches, (2) port and starboard hydraulic flow control, (3) main propulsion thrust direction control, (4) hydraulic selector controls, (5) trim weight position control, (6) main and auxiliary ballast blow and vent valves, and (7) auxiliary ballast manifold valves.

With the exception of the main and auxiliary ballast tank blow vent, and manifold valves, all of the vehicle's operational controls are mechanically linked to their respective functions throughout the vehicle. A detailed description of the vehicle controls, their locations, types, and functions is contained in Table 2.

The vehicle instrumentation, Table 3, has been kept simple. There are pressure gages for monitoring: (1) thrust level of the port and starboard propellers, (2) weight of seawater in port and starboard auxiliary ballast tanks, (3) amount of air in storage tanks, (4) water depth at cockpit level, and (5) amount of pressure-compensating gas. In addition to the gages, there are indicators for determining (1) the relative position of the trim weights, (2) the direction of thrust of the main propulsion motors, (3) the roll angle of the vehicle, and (4) the pitch angle of the vehicle.

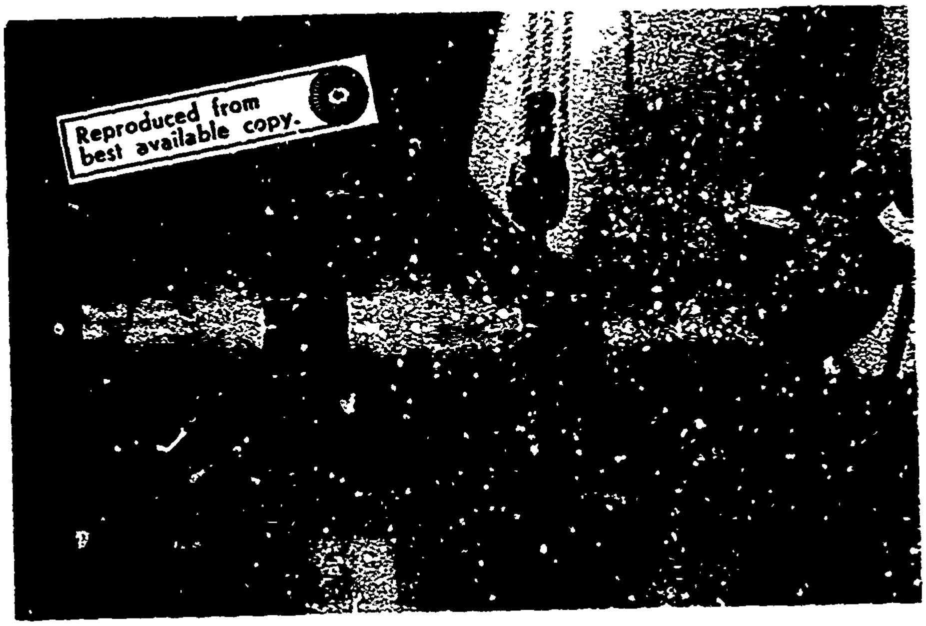


Figure 15. One of the trim weight assemblies.

Detail A

Detail B

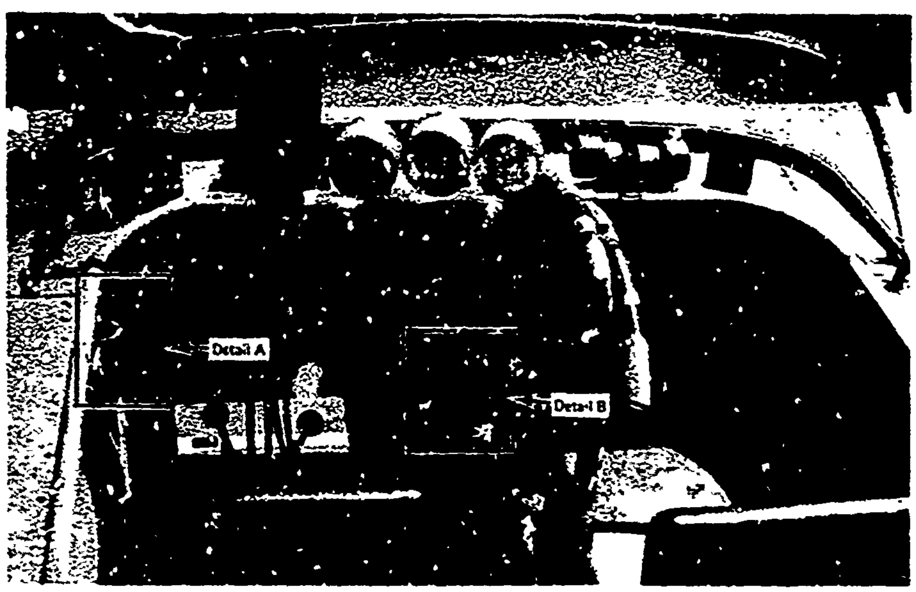


Figure 16. Arrangement of instruments and controls.

Table 2. CAV Control Functions

Control/Instrument	Type	Function	Location	Comment
Electric motor control switch, port and starboard	Levers via push-pull cables to circuit breakers in main motor containers	Turn electric motors on-off	Forward of port diver's seat at elbow height; outer two levers on quad control	Forward turns motor on, port for port motor, starboard for starboard motor; interlocked with pump control to prevent starting motors under load
Hydraulic flow control, port and starboard	Levers via push-pull cables to swash plate lever on hydraulic pump	Vary direction and flow rate of hydraulic oil (thrust level of propeller)	Inner two levers on quad control forward of port diver's seat	Forward of neutral-flow one direction; aft neutral, direction reversed; relative position from neutral determines flow rate or thrust level
Main propulsion thrust direction control	Hand wheel connected via mechanical linkage to rotating main propulsion shafts	Change thrust direction of main propellers to attain vertical thrust	Starboard side of centerline of cockpit just below knee level	Forward on hand wheel directs thrust up; lock keeps rotating shafts in set position
P motor selector	T-level push-pull cable to spool valve under cargo deck	Change from port main propeller to port auxiliary propeller	Mounted on ballast control panel in front of operator	Selects either port main or auxiliary propellers; cannot use both simultaneously
X selector	T-lever push-pull cable to spool valve under cargo deck	Interconnects port to starboard hydraulic systems	Mounted on ballast control panel in front of operator	Use in case of failure of either port or starboard hydraulic system
S motor selector	T-lever push-pull cable to spool valve under cargo deck	Switch from starboard main propeller to starboard auxiliary propeller	On panel to starboard of operator	Selects either starboard main or auxiliary propulsion; cannot use both simultaneously
Pump selector	T-lever push-pull cable to spool valve under cargo deck	Activates auxiliary ballast pump	Mounted in center of auxiliary ballast manifold panel	Pulling lever transfers starboard hydraulic power from propulsion motors to ballast pumps; diver uses starboard hydraulic flow control to vary pumping rate and direction

continued

Table 2. Continued

Control/Instrument	Type	Function	Location	Comment
Trim weight position control	Pneumatic motor via mechanical linkage to trim weights	Correct vehicle trim angles fore and aft	Forward and starboard of operator at waist level	Position of throttle valve on motor determines speed at which trim weights move
Main ballast blow, port and starboard	Three-position, two-way valve	Provides 40 psig air for blowing main ballast tanks	Starboard side of panel in front of operator	Port and starboard blow are separate valves; up for blow
Auxiliary ballast blow	Three-position, two-way valve	Provides a means for calibrating auxiliary ballast tank gages and for emergency blow of tanks	Same valve as starboard main ballast tank blow valve	Port and starboard, both tanks operated from one valve: down for blow
Auxiliary ballast manifold valves	Three PVC ball valves piped to auxiliary ballast tanks	Provides selective flow from auxiliary ballast tanks to compensate for cargo carried and to correct for port and starboard roll	Auxiliary ballast panel in front of operator	Flow schematic included on panel to facilitate selection by operator
Main ballast vent	PVC ball valves piped to tanks	Opens main ballast tanks for submerging	Port side of operator at shoulder level	UP-vent open; DOWN-vent closed; open while submerged; closed on surface

Table 3. CAV Instrument Functions

Instrument	Type	Function	Location	Comment
Thrust level indicators	Standard diver submersible pressure gages, 0-3,000 psi	Monitor thrust level and performance of port and starboard hydraulic systems	Port side of vehicle at operator eye level	Gages provide operator with a visual reference of port and starboard system performance
Auxiliary ballast tank gages	Two standard pressure gages in sealed acrylic housings calibrated in pounds of seawater; 0-750 pounds water (0-15 psi)	Monitor amount of water in auxiliary ballast tanks	Above control panels on vehicle coaming	One gage for each tank; tanks are closed and calibrated to atmospheric pressure while empty; as water is pumped into tanks, pressure head is read in pounds of water ballast
Air storage supply gage	Standard hp air pressure gage in sealed acrylic housing; 0-3,000 psi	Monitor air pressure in storage tanks	Between auxiliary ballast tank gages	–
Depth gage	Standard diver's wrist depth gage	Monitor depth of dive	At operator chest level; one on each side of vehicle	–
Pressure compensation gage	0-3,000-pound diver sea view gage	Monitor gas remaining in pressure compensation bottle	Starboard side of cockpit	–
Trim weight position indicator	Pointer	Determine relative location and movement of trim weights	Mounted on hydraulic thrust level indicator bracket	Operator marks neutral with grease pencil once neutral buoyancy and zero trim has been attained for a specific load
Thrust direction indicator	Pointer	Indicate thrust direction of main propulsion motors	Mounted on hydraulic pressure gage bracket	Indicator calibrated in degrees from horizontal to concur with direction of thrust
Pitch indicator	Liquid-filled curved tube with black ball for gravity positioning; calibrated in degrees	Read out of pitch angle on vehicle	At eye level in front of operator	Two 45-degree mirror surfaces transfer image to divers visual range; instrument has smaller tube for 0 to ±6° readings
Roll indicator	Same as pitch indicator	Read out of roll angle on vehicle	Same as pitch indicator	Single instrument in front of operator

TEST AND EVALUATION PROCEDURES

General

Hydrostatic pressure and functional tests were performed on the vehicle hull structure and system components at the manufacturers. Upon shipment to NCEL, the vehicle was tested to determine conformance with the fabrication and design specifications. These acceptance tests included systems operation to a 120-foot depth. Following the acceptance tests, several sets of operational tests were performed to determine both the vehicle's operational characteristics and utility.

During the course of the test series, modifications were made to the vehicle. The guidelines for these modifications were as follows: (1) insure safety of operators at all times, (2) improve operator control, (3) increase system reliability, and (4) increase vehicle load-carrying capability. The major modifications performed are contained in Table 4.

Test Conditions

Operational tests were conducted in Port Hueneme Harbor and at a protected shallow water site at Anacapa Island.* The support platform was a 50 x 120-foot warping tug equipped with a crane for over-the-side handling. The operational conditions at each site are summarized in Table 5.

Prior to the commencement of operational tests, a comprehensive hazards analysis was performed on the vehicle and its components. The results of the hazards analysis were in the form of procedures, precautions, and modifications to the vehicle; a copy of the analysis is contained in the Appendix.

A detailed dive plan was prepared prior to each underwater operation. The CAV diver—operators were thoroughly briefed on the operation before leaving the support ship. Because of poor visibility at each of the operational sites, direct observation of the submerged vehicle was not possible. Therefore, data on vehicle performance was obtained by debriefing the diver—operators following the dive.

Operational procedures included the following: (1) pre-dive check list to insure all vehicle structural and operational components were in safe operational condition prior to vehicle launching, (2) operational guidelines to insure maximum safety of personnel during vehicle launch and recovery, (3) pre-submergence check of life support air and pressure-compensating gas to insure a sufficient supply was available for the mission, and (4) simplified and detailed mission procedures were established prior to each operation, including extensive diver—operator briefing.

* One of the Santa Barbara Channel Islands located off Southern California.

Table 4. Summary of Major Vehicle Modifications

System/Component	Problem	Modification
Main propulsion thrust direction system	No practical means was available for operators to determine thrust angle of main propellers	• Install thrust direction indicator in operator's visual range
	Main propulsion rotating shafts were not counterbalanced; thus, operator force required for changing direction of thrust was excessive, and units would freely rotate out of set position	• Increase diameter of operator control wheels • Change mechanical gear ratio from 5:1 to 10:1 • Install operator-controlled locking mechanism
Trim weight system	Operational characteristics of vehicle required constant operator trim changes during flight. Operator response using hand-operated system was insufficient to keep ahead of trim changes	• Install pneumatic drill motor in place of hand-operated wheel • Change gear ratio from 10:1 to 30:1
	Operators could not see trim weight indicator provided on vehicle	• Install position indicator in operator's visual range
	Original caster wheels on trim weight assembly broke when they came in contact with small obstructions; thus, trim weights jammed and became inoperable	• Change from hard rubber casters to softer rubber wheels
Hydraulic	Operators could not determine thrust level output of pumps or performance of port and starboard propellers	• Install hydraulic pressure gages—thrust level indicators—in operator's visual range
	Piston accumulators supplied with vehicle to provide a positive head to suction side of hydraulic pumps were ineffective at low pressure range; thus, pumps would cavitate	• Replace piston accumulators with bladder-type accumulators
	Binding of hydraulic lines to main motors would occur when units were rotated, thus increasing diver actuation force	• Add hydraulic swivel connectors
Electric motors	Minor hydraulic oil leakage on motor windings caused deterioration of shellac coatings; thus, ground faults were detected in electrical system	• Clean motor windings and recoat with epoxy varnish

continued

Table 4. Continued

System/Component	Problem	Modification
Batteries	No method was available for monitoring the performance of electrical system during pre-dive procedures	• Install ammeter shunt on each battery with external wet underwater connector
	Bladder containers originally supplied were excessive in size and weight and were not provided with a method for visually checking condition prior to dive	• Replace aluminum containers with lighter weight clear acrylic containers
Pressure compensation system	Regulator supplied with vehicle did not provide adequate flow for compensation; thus, a potential water intrusion problem existed	• Modify demand regulator and plumbing to provide sufficient flow for full compensation at normal descent/ascent rates
	Original intent was to compensate using air; high partial pressure of oxygen presented potential explosion hazard with arcing motors and switches	• Change from air to nitrogen as compensation gas
Motor pump containers	Main mechanical penetrator seals leaked excessively	• Change from cable penetrators to O-ring sealed solid shafts
Main ballast tanks	Operators encountered difficulty in completely venting tanks because of piping arrangement; air bubble remaining in tanks caused trim and buoyancy control problems	• Move vent openings to forward and aft end of tanks and increase piping size to reduce line restriction
Electric motor and hydraulic pump controls	Vehicle was supplied with a single lever for operating each electric motor and hydraulic pump; system was unreliable because of excessive linkage clearances	• Change to independent levers for pump and motor with a mechanical interlock to prevent starting of electric motors under load
Operator seats	Original seats were uncomfortable for effective diver use	• Install adjustable seats with scuba tank supports and back rests
Seat belts	Diver actuation of vehicle controls was difficult because of neutral buoyancy of diver	• Install seat belts to enable divers to stay in place while operating controls

Table 5. Operational Conditions at Test Sites

Condition	Test Sites	
	Anacapa	Port Hueneme
Maximum depth (feet)	110	35
Total operational time (hours)	21	47
Number of dives	43	65
Visibility (feet)	10 to 35	2 to 5
Water temperature (^oF)	55	55
Swell condition (feet)	1 to 5	0 to 1

All CAV operational tests were performed under rigid safety guidelines. Operations were terminated when either operational conditions or vehicle performance indicated possibility of personnel hazards. The majority of the vehicle tests were performed in a free, untethered mode. The test sequence included: (1) vehicle operational characteristics, (2) mission performance, and (3) interface testing with other closely related underwater tools and systems.

The determination of operational characteristics was performed in conjunction with diver-operator training. Surface, submerged, and interface stability tests were performed initially. These tests were performed with the CAV tethered to the support ship until confidence was gained and the procedures became routine.

Once it was determined that the vehicle was operationally stable and controllable, mission performance testing was conducted. Cargo was carried to and from underwater work sites, tools were operated from the vehicle, and minor construction tasks, such as assembly of split pipe, were performed.

TEST RESULTS

The surface and submerged characteristics of the CAV are discussed below for both the static case (where the vehicle is not under power) and for the dynamic case (where the vehicle is being propelled). In addition, the performance of the vehicle during the transition from the surface condition to the submerged condition (interface translation) is discussed. The majority of the vehicle components functioned without major failure. Results of tests on major vehicle components are summarized in Table 6.

Table 6. Results of Performance of Systems and Components

System	General Results	Major Component	Specific Problems and Comments
Electrical	The majority of vehicle down time was associated with failures in this system Sufficient power was available to operate within design specifications	Batteries	The oil pressure-compensation system consistently spilled oil, impairing diver's vision and making walking surfaces dangerously slick Seawater entered battery boxes through relief valves, causing grounding problems
		Electric motors	Consistent grounding problems were encountered from contamination with leaked hydraulic oil and carbon from excessive brush wear
		Cables and connectors	Grounding problems were encountered with seawater entering connector
Hydraulic (oil)	The system functioned without fault during majority of vehicle tests	Pumps	Supplied sufficient power and control for vehicle operation
		Motors	Functioned exceptionally well under all conditions
		Valves	Minor leakage occurred in spool valves

continued

Table 6. Continued

System	General Results	Major Component	Specific Problems and Comments
Compressed air	The system provided sufficient air for vehicle operations	Pressure regulator	Excessive time was required to blow main ballast tanks (approximately 15 minutes)
Main ballast tanks	Tanks provided sufficient buoyancy for surface stability	Vent system	Complete vent of system required operators to obtain a 15-degree stern down angle prior to submerging
Auxiliary ballast	The system operated without failure and provided adequate volume for cargo handling The free surface effect required operators to continually adjust vehicle trim	Tanks	The free surface effect caused pitch angle control difficulties
		Pump	Rate of ballast change was very slow, approximately 100 lb/min
		Gages for monitoring	Calibration problems existed because of change in surrounding environment temperature
		Site gage	Very difficult to read underwater
Trim weight	Provided sufficient trimming moment for most vehicle operations	Hand wheel	Required excessive diver force to keep ahead of vehicle trim
	Trimming response with air motor was approximately 140 ft-lb/sec	Pneumatic motor	Excellent response for trim correction; control and instrumentation was confusing to operator

continued

Table 6. Continued

System	General Results	Major Component	Specific Problems and Comments
Main propulsion units	Thrust position located above center of drag and aft of vehicle center of gravity, thus, excessive trim requirements needed by operators	Thrust direction control	Units not counterbalanced; thus, excessive force required by operators to change position
	Depth control while translating horizontally very difficult	Speed and steering control	Operators had excellent control over vehicle thrust control and steering
Auxiliary propulsion units	Performed exceptionally well for surface maneuvering Required constant pitch control for submerged translation	–	–
Pressure compensation	System operated effectively for all operational situations	Regulator	Provided sufficient flow for compensation
Attitude indicator	Functioned well during tests; needs to be more readable by divers.	Pitch indicator	Operators had difficulty reading in turbid water
		Roll indicator	Worked very well
Gages	All gages functioned well during tests	Depth gage	Operators had problems reading in turbid water and interpreting small changes in depth
		Air pressure gage	Difficult to read; diver needed to move closer to get accurate readings

The normal surface condition of the vehicle is with approximately 5,000 pounds of net buoyancy, which is carried in the main ballast tanks. When submerged, the main ballast tanks are completely flooded, and the vehicle becomes neutrally buoyant. In the neutral buoyancy condition, approximately 1,300 pounds of ballast is carried as either water in the auxiliary ballast tanks or as wet weight cargo. Any combination of water and cargo that totals 1,300 pounds can also be carried. This ballast is normally carried during surface operation of the vehicle.

Handling

A three-point sling lifted the CAV from the water to the surface support ship. Numerous drain holes were provided on the bottom fairings to insure rapid water drainage while the CAV was being lifted. Normally, the CAV was lifted with the main ballast tanks dry (20,000 pounds). However, one test was performed in 3- to 4-foot seas with the tanks flooded. A dynamometer attached to the lifting sling indicated that a maximum dynamic load of 29,000 pounds was attained.

Surface Stability

Static. The CAV was stable on the surface. The vehicle responded slowly to unbalancing forces from surface swells. On one occasion pitch angles of up to 2 degrees and roll angles of 5 degrees were experienced in 3- to 4-foot seas.

As the vehicle experienced various pitch angles, some air was spilled from the open [illegible] at the bottom of the main ballast tanks. This air spillage reduced the net surface buoyancy of the vehicle but was not significant in normal operation.

For small pitch and roll angles the CAV was found to have a metacentric height of 7.5 feet longitudinally and approximately 3 feet transversely. These values take into account the gas spillage for angles up to 5 degrees and the free surface effect produced by the auxiliary tanks for the same angles. If an upsetting moment of approximately 20,000 ft-lb in pitch was experienced, considerable air would spill from the main ballast tanks. For example, if an upsetting moment was produced by adding a 2,500-pound point load to the center of the cargo deck of the trimmed CAV prior to submergence, the angle produced would be sufficient to cause stability problems. However, upsetting moments of this magnitude would not be experienced during normal vehicle operations.

Dynamic. The CAV was stable while surface translating. Because of the low vehicle freeboard, some operator discomfort was experienced when water broke over the water shield. As a result, stern-to-the-sea translation was preferred by the operators.

The surface hydrodynamic characteristics of the vehicle resulted in a bow burying tendency, as shown in Figure 17. This condition was most predominant when traveling at the maximum surface speed of 2.8 knots. Although the bow wave limited the vehicle's maximum speed, the speed attained was sufficient for the intended operations.

Surface maneuverability was found to be very good. The operators turned the vehicle in place at rates up to 180 deg/min. Turning while under way, although good, was very gradual. The turning radius approached zero as the forward speed approached zero. The stopping distance at maximum speed was found to be approximately 40 feet.

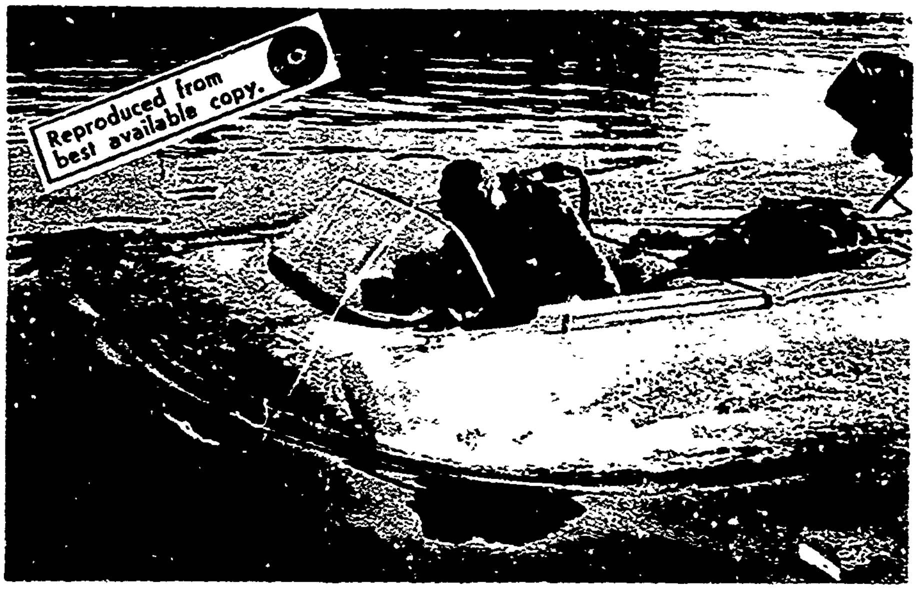


Figure 17. Bow wave formed by CAV at a 2-knot forward speed.

Interface Translation

The CAV was stable during submergence, even though the center of buoyancy moved from below the center of gravity to above the center of gravity. The reason for this stability is that the vehicle has adequate freeboard (buoyancy) when the center of buoyancy and the center of gravity coincide.

Thus, if an upsetting moment is encountered at this point, the center of buoyancy shifts to produce a righting moment. After the CAV was submerged, it rode under the surface quite well. The weight of the main propulsion units drove the CAV cockpit 2 to 3 feet below the trough of surface waves (3 to 4 feet in height), thus keeping the operators out of surface wave action.

Horizontal translation tests were made with the CAV neutral and the Kort nozzles awash. Slow ahead on the auxiliary propulsion system (lower propellers) caused the CAV to pitch up slightly and ride with the water shield awash. Going ahead on the main propulsion system (upper propellers) with the Kort nozzles horizontal caused the bow to pitch down.

The operators can surface the vehicle by driving up with the main propulsion units vertical (for example, like a helicopter), or they can also surface with the main propulsion units horizontal (or with the auxiliary propulsion units) by attaining a trim-up angle. In any case, blowing the main ballast tank is initiated just before the boat breaks the surface. The CAV was found to be very stable during all forms of surfacing. Additional surfacing tests were performed by blowing the main ballast at 20-foot depths. The vehicle surfaced with either a bow-up or bow-down angle of approximately 20 degrees, but it was stable in all cases.

The most desirable method of surfacing was driving up on the main propulsion system. In this mode, the operator had the most control over stopping his ascent, in case he should find himself coming up under a surface vessel.

Submerged Stability

Static. The primary measure of submerged stability is the distance between the center of gravity and the center of buoyancy, called BG. For the CAV, this value was experimentally determined to be 5.5 inches. However, this value was reduced to an effective value of 2.1 inches (in pitch) because of the free surface effect. The auxiliary ballast tanks produce a free surface effect. When less than a full load of cargo is carried, these tanks are partially full of water. Because of the 6-foot-length of each tank, free liquid surface-induced moments of approximately 1,000 ft-lb can be experienced for 10-degree angles. Figure 18 illustrates the CAV's righting moment as a function of angle for the case with the free surface effect (water in the auxiliary ballast tanks) and for the case without the free surface effect.

While the vehicle was submerged, the free surface had the apparent effect of reducing the BG to 2.1 inches, a 62% reduction. As a result, pitch control was more difficult.

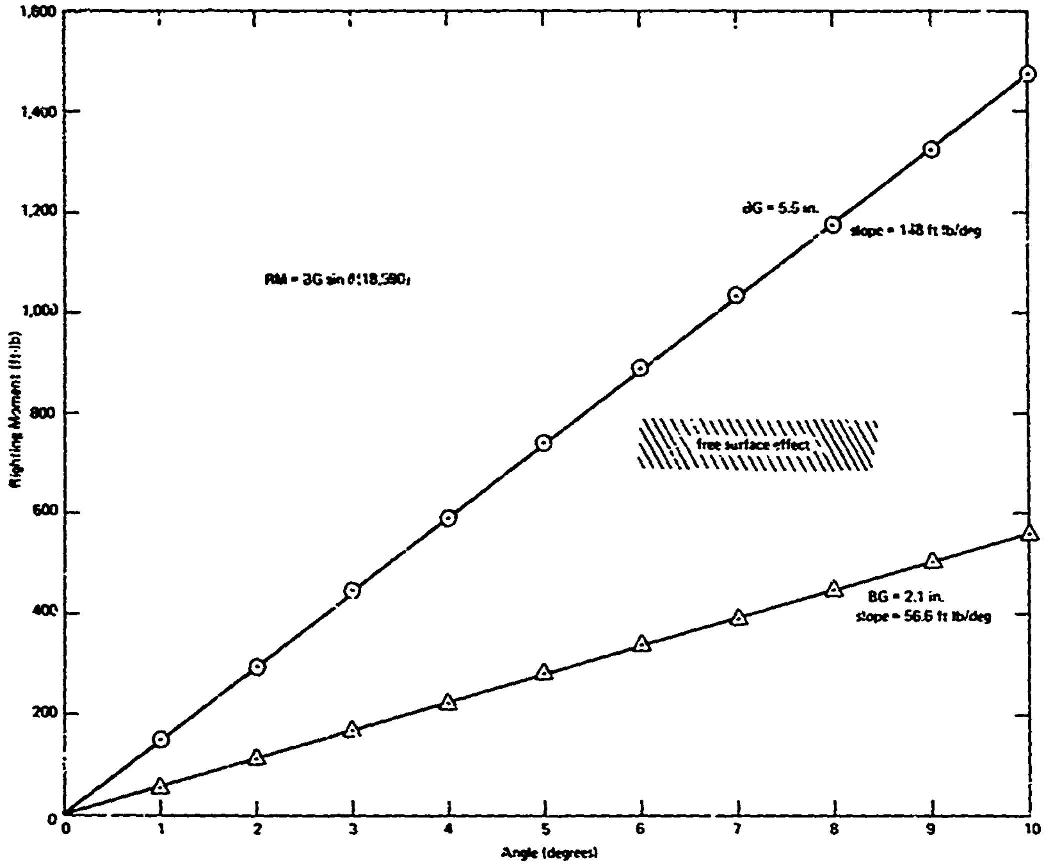


Figure 18. CAV submerged righting moments as a function of vehicle pitch angle.

Dynamic. The CAV can be driven vertically in the water column by powering straight up or straight down on the main propulsion units. A vertical thrust of approximately 300 pounds is available. Maximum vertical speeds were found to be about 60 ft/min (the CAV neutrally buoyant). The resultant vertical center of drag was ahead of the main propellers, which caused a bow-up angle hile driving down and a bow-down angle while driving up. Pitch angles of ..out 8 degrees were encountered when full power was used to descend/ascend. The vertical stopping distance was found to be 8 feet.

Maintaining a specific depth in the water column (hovering) was relatively easy. With the CAV properly ballasted, very little control was required to stay within 1 to 2 feet of depth.

Submerged horizontal translation can be accomplished with either main or auxiliary propulsion systems. The boat was designed to be normally operated using the main propulsion units while underwater. Since the main propulsion units are located above the main structure, a pitch down would be expected during forward translation; this did occur when thrust was initially applied. However, as the boat gained forward way, a slight pitch up tendency was produced. The pitch up is due to a hydrodynamic planing effect. If the CAV is started from a level trim submerged, it will initially pitch down between 5 and 10 degrees (depending on the power setting) and then pitch up from 2 to 8 degrees. Then it will pitch back to a stable bow-up angle of anywhere from level to several degrees (depending on cargo drag, primarily).

If the operator does not correct trim during forward translation, the CAV will oscillate within approximately a 20-foot-depth range. With trim weight corrections he can maintain trim within several degrees and easily maintain depth to ±5 feet (±2-1/2 feet during acceleration to one-half power). Slight trim corrections (trim weight displacements) are occasionally required for depth control and must be anticipated after speed changes or steering corrections.

The original concept was to control the vehicle depth by regulating the direction of thrust of the mains. A half-speed run was made using this technique, starting from a level trim submerged. When the vehicle stabilized, a trim of 10 degrees up was encountered with the mains pointed 55 degrees down. Depth control during forward translation was found to be more effective using the trim weights.

The CAV was found to be stable in yaw submerged and required no more steering correction than most 30-foot surface craft. The thrust level indicators facilitated power settings for straight flight or gradual turns. The CAV operators were able to turn the vehicle in place quite readily while submerged. Roll angles of 2 to 3 degrees and pitch angles of about 10 degrees were experienced during turns in place.

The auxiliary propulsion units can be used for underwater translation too. However, the auxiliaries are not as efficient, because they are located behind the main ballast tank structure that produces turbulent flow into the propellers. Submerged propulsion via the auxiliaries causes more of a tendency to pitch up than the mains. Therefore, a greater trim weight correction is required to maintain pitch and depth. Translation with the auxiliaries is similar to that with the mains.

Operational and Mission Performance

Operational tests were performed to determine the utility of a CAV-type vehicle for supporting diver construction tasks. The specific tests and results are summarized in Table 7.

Table 7. Operational Tests

Test	Procedure	Results
Towing test	Vehicle was towed in open sea using a 40-foot utility boat; 3- to 4-foot seas, 1- to 5-knot winds	Vehicle towed well at speeds up to 5 knots. At greater speeds, water taken over the bow could damage vehicle components
In water replenishment	Vehicle was operated for two days without removing it from water	Electrical connectors became contaminated with seawater, causing grounding problems and potential shock hazards
Bottom maneuvering	The CAV was maneuvered with the landing skegs in contact with seafloor	No appreciable problems were encountered; very effective in areas where there are no bottom obstructions
Limited visibility site location	Operators utilized a visual reference line attached to work site and surface buoy to locate bottom site in poor visibility water	Technique very effective for site location without navigational aids
Surf zone translation	Vehicle was surface translated through mild surf (0 to 2 feet) in a protected harbor to determine operator control capabilities. Vehicle was beached on forward end of landing skegs and recovered under own power.	During test, port hydraulic system failed due to broken mechanical linkage. Operators were able to perform beaching and recovery; however, steering control was extremely difficult because of failure
Operation of hydraulic tools at seafloor construction site	Several hydraulic tools were operated from vehicle power source; tools included: (1) impact wrench; (2) winch; (3) rock drill; (4) cable cutter	The CAV power source provided sufficient power to operate most commercially available tools; the vehicle as a movable power source was proven to be very effective
Load handling from cargo bed	70-pound sections of split pipe were loaded and unloaded at an underwater site	No problems were encountered with handling cargo. The cargo bed was found to be very effective for diver use
Transport divers	Divers were transported from the support craft to the underwater construction site	Divers need some protection from direct prop wash

Seabee underwater construction teams are presently involved in the underwater installation of cast iron split pipe. The pipe is used to protect oceanographic cables from chaffing on ocean bottom coral and rock. Each split pipe section has an underwater weight of approximately 70 pounds. The diver's task is to move, position, and assemble the pipe over the submerged cable. Standard 5/8-inch bolts are used to connect the pipe section together. In addition, the split pipe sections are sometimes anchored to the ocean bottom by drilling and grouting U-bolts in the seafloor rock.

On two occasions, sections of pipe were carried to a predetermined underwater site by the CAV. The pipe was unloaded by the vehicle operators, and the empty vehicle was returned to the surface to simulate picking up another load of cargo. In addition, the operators returned to the work site, loaded split pipe onto the vehicle, and returned to the support ship.

The operation involved: (1) locating the ocean bottom work site in less than 5-foot visibility, (2) changing vehicle buoyancy to accommodate cargo removal and addition, and (3) physically removing, adding, and securing cargo to the cargo deck.

Because of limited visibility at the site (40-foot depth) a buoy descending line was used for reference by the vehicle operators. Once on the bottom, a third diver directed the CAV operator in maneuvering the vehicle so that the cargo bed was at the required location. This was readily accomplished within a 2-ft^2 area.

The CAV was ballasted prior to the removal of the cargo and deballasted following cargo addition. Because of the slow response of the vehicle to buoyancy changes, the addition and removal of ballast was easily accomplished. The vehicle operator monitored the depth gage during deballasting to determine when a slight positive buoyancy was attained. Operators had no problems in changing vehicle buoyancy to accommodate for cargo changes.

Several hydraulic tools were operated from the vehicle power supply. Figure 19 shows a diver operating a hydraulically powered winch attached to the vehicle cargo bed. The free end of the winch cable was attached to an eye on a rock bolt; the bolt was placed by the diver using the experimental hydraulic rock drill shown in the figure. This operation was conducted in shallow water (10-foot depth) to simulate working in a surge area. The CAV was ballasted approximately 200 pounds heavy on the bottom to insure a stable work platform. The mild surf present produced a surge current of approximately 1 to 1-1/2 knots. The divers had no difficulty in operating the CAV or the tools in this condition. The vehicle power supply provided ample power to operate the hydraulic tools. Figure 20 portrays various operational situations of the CAV.

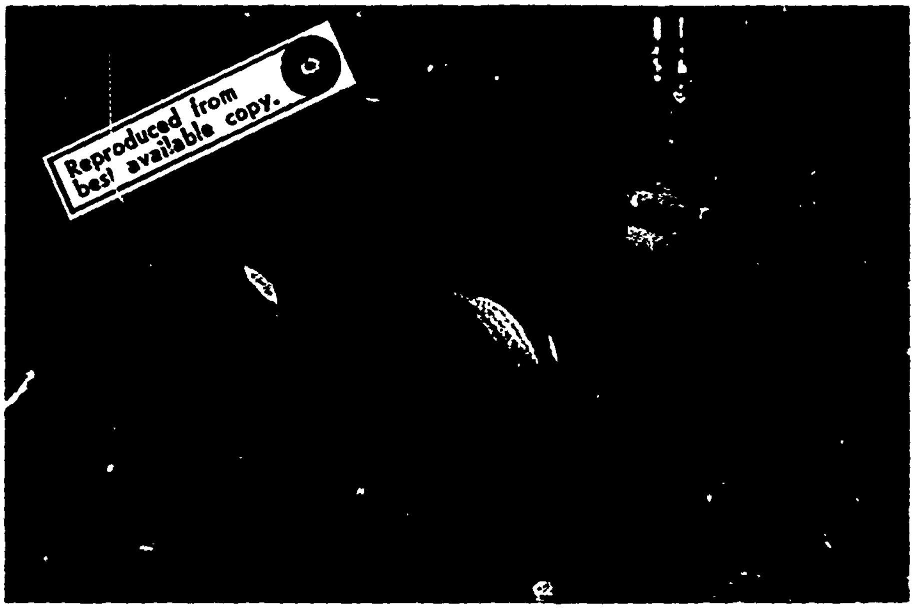


Figure 19. Diver operating hydraulically powered winch mounted on CAV cargo bed; experimental hydraulic rock drill shown on right side of winch.

Summary

1. Stability and operational tests proved the CAV to be a stable platform from which divers can perform underwater work.

2. The majority of the vehicle components functioned without major failure. Results of tests on major vehicle components are summarized in Table 7.

3. The electro-hydraulic propulsion system provides excellent control over vehicle speed and turning.

4. The movable weight system is an excellent method for controlling vehicle trim angles. Depth control while translating horizontally is only marginally acceptable and is best controlled by utilizing the movable trim weight.

5. Because of the displacement of the center of thrust with the vehicle center of drag, horizontal translation requires excessive trim adjustments by the operator.

6. Vertical propulsion for both hovering and depth control is excellent. However, the operator's visual reference to the ocean bottom is poor because of structural obstructions.

7. Ballast control utilizing seawater and closed tanks is relatively simple and effective.

8. Cargo handling utilizing an open cargo deck is simple and effective.

9. The CAV propulsion system provides adequate power to effectively operate hydraulic tools. In addition, ample compressed air is available for operation of pneumatic tools.

10. Utilizing the CAV as a mobile base for diver construction operations requiring cargo and tools proved to be very effective.

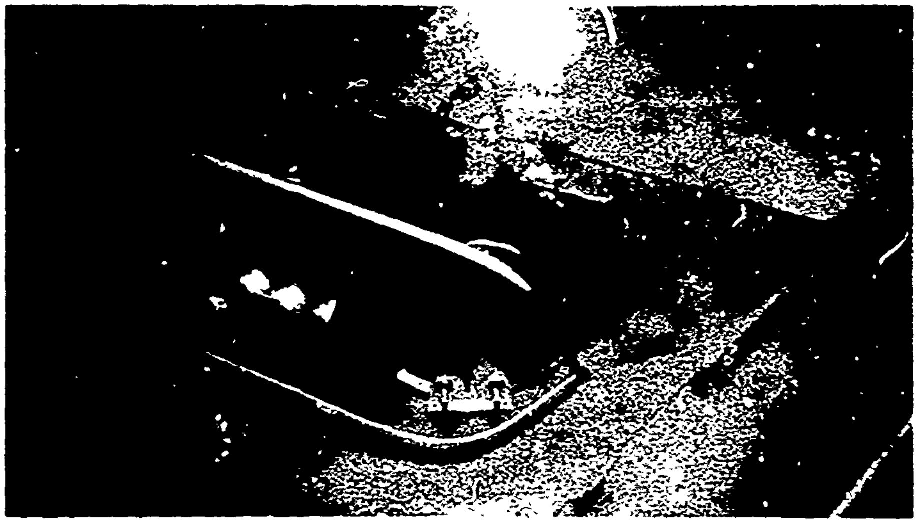
11. Operator maneuvering control for locating underwater construction sites is easily accomplished utilizing the CAV. In addition, operating and maneuvering in limited visibility utilizing a reference line is easily accomplished.

EXTENSION OF CAV CAPABILITIES

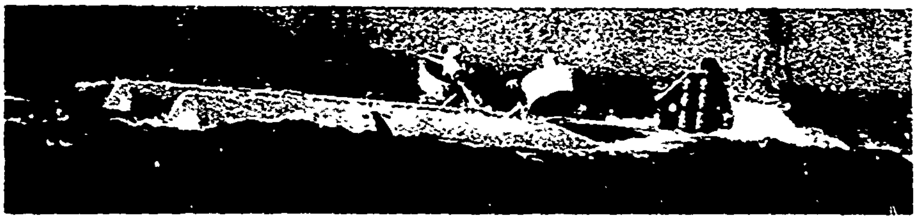
The experimental CAV has been proven to be an effective diver construction aid for carrying construction equipment (tools and materials) to the ocean bottom work site and for supporting the working diver. The mobility of the vehicle affords the diver with a means of selecting and changing underwater work sites without surface support. Tools, power supplies, and cargo can be readily located at the working diver's option. Sufficient battery power is available to operate the vehicle at maximum speed (2.5 knots) for approximately 4 hours. In a construction operation, where hydraulic tools are operated from the vehicle power supply during 50% of the total operational time, sufficient power is available to maneuver the vehicle a distance of from 5 to 7 miles before requiring surface support for system replenishment.

Power sources for operating tools are presently located on the surface support vehicle. Cargo and supplies are either lowered to the bottom by the support ship or carried by divers using lift bags. In both cases, as surface conditions deteriorate, operations become hazardous, and existing equipment becomes ineffective. In some cases, only small boats (up to 15 feet in length) have been available for surface support. In these instances, working divers must rely on hand tools and hand lowering lines for construction aids.

(1) CAV being used for surface transportation of construction divers.



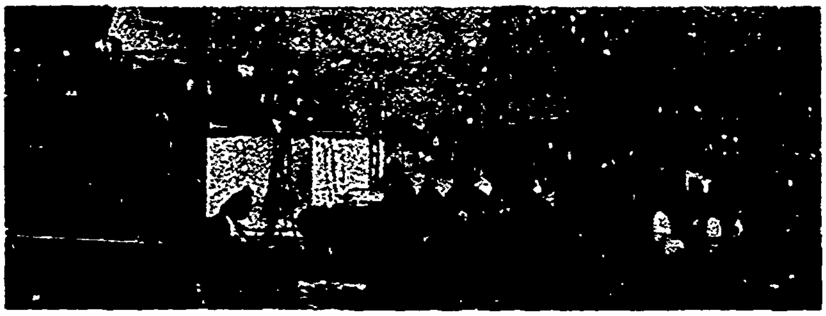
(2) Operators maneuvering CAV during 110-foot test dive. Bubbles are being exhausted from pneumatic trim weight motor.



(3) White water being taken over bow in 3-foot seas. Note main propulsion motors set for vertical dive.

Continued

Figure 20. CAV in various operational conditions.



(4) CAV being lowered into water from NCEL warping tug.

(5) CAV being lifted from water. Note water draining from trim weight tubes.

(6) CAV cargo bed containing split pipe cargo. Battery compensation bladders shown in foreground.

Figure 20. Continued.

More recent operations involve the installation, stabilization, protection, and repair of oceanographic cables. These installations necessitate the movement of support equipment along the predetermined ocean bottom cable route. Accurate placement of the materials and equipment is essential. As an example, holes must be drilled in ocean bottom rock and coral for placement of explosive charges used in site preparation and for subsequent placement of cable stabilizing anchors.

The underwater construction teams presently utilize a pneumatically powered crawler rock drill designed for land use and have found it to be extremely unreliable underwater. In addition, its bottom crawling capabilities are extremely poor because of the irregular terrain encountered. The drill is often wedged on outcroppings and ravines. Movement of the track drill over large obstacles requires the use of either a surface support ship or pontoon lift bags. In either case the operation is time consuming, inefficient, and hazardous.

With some modification and extension of the CAV concept, an effective submersible work platform could be designed and fabricated. The end product would be a diver work vehicle capable of optimally supporting the majority of diver construction operations.

Most types of hydraulic tools can be operated from the CAV power supply. Large or heavy tools could be mounted on the cargo deck, thus utilizing the vehicle for placement at the site. A bottom crawling capability incorporated with the vehicle's present capabilities would enable the working diver to more accurately place the cargo or work equipment. The present capability to translate horizontally and vertically would enable the diver to easily surmount bottom obstacles. The speeds and endurance of the vehicle now are more than adequate for anticipated diver construction operations. The payload capability should be increased to a minimum of 2,000 pounds.

In remote areas where surface support vessels would not be available, it is essential that the CAV prototype have a capability of translating to shore either under its own power or with minimal land or surface support. Finally, transportation of the CAV from the home port to remote geographical locations requires that the size and weight of the vehicle be reduced to permit air shipment.

COMPARISON WITH OTHER DIVER SUPPORT SYSTEMS

Various types of wet vehicles for supporting scuba divers are presented in Table 8. Swimmer Propulsion Units (SPU) provide only transportation. Swimmer delivery vehicles provide a limited cargo-carrying capability in addition to diver transportation. The Buoyancy Transport Vehicle (BTV) and the

CAV are the only known diver-operated vehicles that supply power to operate the working diver's tools. The BTV complements a CAV-type vehicle in that it accommodates the movement of large cargo loads on the bottom. In summary, the CAV is the only vehicle which provides the working diver with *total* bottom support.

CONCLUSIONS

1. The present experimental vehicle provides a stable platform which can be safely used by scuba divers for the support of underwater construction operations. The experimental vehicle can also be effectively used as a test bed for the evaluation of underwater tools and work techniques. Conclusions on major vehicle systems are:

a. An electro-hydraulic power system is an effective means of providing vehicle propulsion and tool power.

b. A simplified control system with no hydrodynamic control surfaces is an effective means for maneuvering a slow-moving CAV-type platform.

c. A rotating propulsion system, as designed for the present vehicle, that provides both vertical and horizontal thrust is unsatisfactory. Independent vertical and horizontal thrust proved to be more effective.

d. A seawater ballast system is a simple and effective method to compensate for vehicle buoyancy changes resulting from removal or addition of cargo. Future systems should be designed to minimize the adverse trim effects resulting from the presence of a free liquid surface.

e. A simplified instrumentation system, as presently configured, is effective in operational situations where high speed (above 2.5 knots) and long distance navigation (beyond direct visual reference) is not required. Blind navigation (visibility limited to a minimum of 3 feet) can be successfully accomplished using a buoy-type reference line.

2. Mission performance tests have shown that the CAV concept of an underwater "pickup truck" capable of carrying all necessary tools and equipment is an effective means of supporting the working diver. Specifically:

a. The elimination of power umbilicals (for diver tools) from surface support vessel provides the working diver with more freedom and safety at the underwater work site.

b. The use of an open cargo deck for storing cargo and tools is especially effective for diver operations. The presently used techniques associated with handling small items, such as tools and split pipe, and even items up to 500 pounds that can be handled with lift bags are especially adaptable to this type of vehicle.

c. Cargo weighing more than 500 pounds and bulky items which require loading or off-loading by divers can best be carried under the CAV. However, the drag effects from bulky items appreciably reduce the operator's ability to maneuver the vehicle while it is translating horizontally.

d. Surface translation and submerged vertical and horizontal translation are essential for diver placement and location at the desired underwater site. In addition, an ability to track (crawl) along the seafloor is necessary for precise bottom location, such as would be encountered during a cable stabilization task.

e. Surface replenishment of the CAV systems can be accomplished from a support vessel such as an LCM-6. However, in remote areas where a surface support vessel would not be available, the diver vehicle should have a capability to translate through mild surf (3 to 4 feet) to shore either under its own power or assisted from shore.

3. The use of a cockpit mockup for instrumentation and control arrangement together with the application of human factor guidelines is essential for a successful vehicle design.

RECOMMENDATIONS

1. For the present experimental CAV to be utilized in support of diver construction operations, or in conjunction with test and evaluation of research-type tools and work techniques, it is recommended that the following modifications be made:

a. The present electrical system should be modified to provide greater reliability. Electrical connectors should be better sealed to prevent seawater intrusion; electrical motors should be coated for protection from contamination by carbon and for minor oil leakage.

b. Some additional human factors engineering and redesign of the vehicle controls and instrumentation needs to be performed to provide easier operator control: integrate the pitch, roll, and depth indicators into a single centrally located display; provide a compass for operator visual reference on directional control; increase size of thrust control indicators.

c. The main propulsion units should be counterbalanced to provide easier diver actuation.

Table 8. Comparison of We

Description	General Function	Diver Support Functions	Propulsion System	Maximum Submerged Speed (knots)	Operational Time at Maximum Speed	
Construction Assistance Vehicle—experimental	Designed as an experimental diver support platform equipped with tools, power sources, and cargo area	1. Carry tools and cargo underwater 2. Power tools 3. Transport divers 4. Stable bottom platform	vertical horizontal surface hover turn in-place	2.5	4 hours	v li c
Construction Assistance Vehicle—prototype	Extension of experimental model to include interchangeable work modules for drilling, excavating, cable installation, stabilization, etc.	Same as above plus 5. Crawl on bottom 6. Translate through mild surf (3-4 ft) 7. Heavy work functions such as drilling, coring, excavating	vertical horizontal surface bottom crawl dry land surf zone	1 to 2	4 hours	v a f g t a
Buoyancy Transport Vehicle—experimental	Designed to prove concept of free swimming vehicle that provides forklift or yard crane functions at an underwater site, i.e., transport and position relatively large payloads	1. Transport and position payloads (on bottom) 2. Power tools (limited capability)	vertical horizontal surface hover	1.3	1 hour	v
Buoyancy Transport Vehicle—(projected data) prototype	Underwater forklift/yard crane, move and position relatively large payloads	1. Transport and accurately position large (multi thousand pound) payloads 2. Provide hydraulic power for tools	vertical and horizontal, surface and submerged	1.5	unlimited on umbilical—1 hr on batteries	v li c
Swimmer Propulsion Units	Designed for transportation of a single diver, commercially available units mostly designed for recreation	1. Transport divers 2. Visual survey or photography	horizontal surface	2 to 3	1.4 hours	u v
Swimmer Delivery Vehicle, "Shark Hunter," commercial	Designed to transport two divers, tools, and limited cargo to and from underwater sites.	1. Carry divers and tools to underwater work site 2. Survey bottom	horizontal surface	2 to 4	1.3 hours	v
Swimmer Delivery Vehicle	Several commercial models available, military models provide increased speed, endurance, cargo, and cost	-				
Surface Support Platform	Ship or other moored platform with compressors, generators, etc., mounted on deck	1. Support working diver 2. Tools and lifting positioning limited by sea state 3. Divers burdened by umbilicals	Surface and possibly a sled towed under water for survey	N/A	N/A	s s s t

A

Table 8. Comparison of Wet Submersibles for Supporting Scuba Divers

Propulsion System	Maximum Submerged Speed (knots)	Operational Time at Maximum Speed	Navigational Capability	Maintainability	Payload Capability	Tool Power	Dry Wt (lb)	L x B x H (ft)	Operating Depth (ft)	C
tical rizontal face ver n-in-place	2.5	4 hours	visual and limited compass	during operational period requires one skilled technician half time	1,300 lb in 4 x 7-ft cargo bed or sling underneath	12 gpm at 1,200 psi (oil hydraulic), 20 cfm pneumatic	18,630	26 x 9½ x 7½	130	variable spe steering and control by p fabricat.on S75,000
tical izontal face tom crawl land f zone	1 to 2	4 hours	visual/compass, adaptable to future developments, such as transponders and pingers	designed for compatability with fleet, low maintenance, performed in the field by fleet personnel	2,000 lb in cargo bed or lift	total power to vehicle ~ 20 to 50 hp, power can be directed to diver tools (hydraulic)	10,000 to 15,000	–	diver limited	All specifica derived for performanc both land a specificatio preliminary
tical izontal rface wer	1.3	1 hour	visual	one technician full time (large part of effort is maintenance of surplus silver zinc batteries)	1,000 lb on cargo hook	6 gpm at 1,800 psi (oil hydraulic)	1,800	8 x 6 x 6	850	Steering an by propulsi by dewater
rtical and rizontal, rface and ome. jed	1.5	unlimited on umbilical— 1 hr on batteries	visual plus limited compass	low man hour requirements	3,000 lb can be supplemented by modular buoyancy packages	10 gpm at 2,000 psi	2,500	8 x 8 x 8	130	Steering an propulsion buoyancy system inc design
rizontal rface	2 to 3	1-4 hours	usually direct visual	relatively low maintenance because of simplicity of vehicle	none	none supplied	50 to 100	3 x 1 x 1	150	Primarily d propulsion $400 and
rizontal rface	2 to 4	1 3 hours	visual	low maintenance because of simplicity of structure and components	usually inside vehicle	none supplied	1,200 to 2,500	16 x 8 x 5	150 to 300	Step speed and depth and rudde $500,000
	–	–		–	100 to 300 lb, 5 to 10 ft^3	-		-		–
rface and ssibly a sled wed under ter for survey	N/A	N/A	standard surface ship techniques	standard ship maintenance, performed by normal diver	ship lift capacity	limited only by size of umbilical diver can carry	N/A	N/A	N/A	Support c safety fau state and

uba Divers

Payload Capability	Tool Power	Dry Wt (lb)	L x B x H (ft)	Operating Depth (ft)	Comments
1,300 lb in 4 x 7-ft cargo bed or slung underneath	12 gpm at 1,200 psi (oil hydraulic), 20 cfm pneumatic	18,630	26 x 9½ x 7½	130	variable speed control, steering and depth control by propulsion; fabrication cost $75,000
2,000 lb in cargo bed or lift	total power to vehicle ~ 20 to 50 hp, power can be directed to diver tools (hydraulic)	10,000 to 15,000	–	diver limited	All specifications preliminary, derived for interpolation with performance of existing vehicle; both land and underwater final specifications will follow preliminary design
1,000 lb on cargo hook	6 gpm at 1,800 psi (oil hydraulic)	1,800	8 x 6 x 6	850	Steering and depth control by propulsion; buoy control by dewatering sphere
3,000 lb can be supplemented by modular buoyancy packages	10 gpm at 2,000 psi	2,500	8 x 8 x 8	130	Steering and depth control by propulsion motors, automatic buoyancy or depth control system incorporated into design
none	none supplied	50 to 100	3 x 1 x 1	150	Primarily designed as a propulsion device, cost $400 and up
usually inside vehicle	none supplied	1,200 to 2,500	16 x 8 x 5	150 to 300	Step speed control, steering and depth controlled by planes and rudders, cost $5,000 to $500,000
100 to 300 lb, 5 to 10 ft^3	–	-	-		-
ship lift capacity	limited only by size of umbilical diver can carry	N/A	N/A	N/A	Support of diver limited by safety factors relating to sea state and umbilicals

B

C

2. With the test bed vehicle described herein, the CAV concept was proven to be safe and effective. The CAV concept should be carried through to a prototype design, fabrication, and evaluation. The prototype vehicle should have the following characteristics:

a. Utilize off-the-shelf components in fabrication.

b. Reduce size and weight over present configuration, while maintaining a 2,000-pound cargo-carrying capability. A 25% reduction should be practical without substantial cost increases.

c. Redesign power system to:

(1) Provide independent vertical and horizontal thrust capabilities.

(2) Power trim weight adjustment by utilizing hydraulic system.

(3) Improve electro-hydraulic system reliability by designing a system utilizing an oil-submersible electric motor.

(4) Provide independent power ballast control for cargo compensation with a minimum 300-lb/min rate.

d. Incorporate a bottom crawling capability for accurate bottom maneuverability.

e. Provide an amphibious capability to translate through limited surf (3 to 4 feet) to shore to accommodate system replenishment or loading and unloading in remote areas where surface support is inadequate. Surf zone translation may be accomplished while in the bottom crawling mode and perhaps with the vehicle unmanned.

f. Provide the CAV with a capability of being towed at a minimum speed of 5 knots.

g. Insure that the vehicle can travel submerged at a speed of 2.5 knots (zero current) for a duration of 2 hours and, in addition, can provide sufficient power to operate a 6-gpm hydraulic tool for 2 hours. It should also have the capability to travel on the surface at a maximum speed of 2.5 knots.

h. It is highly desirable that the vehicle be completely capable of surface in-water replenishment of all consumable systems.

Appendix

HUMAN FACTORS STUDY

During all stages of the development and evaluation of the CAV a considerable amount of effort was directed towards human engineering of diver operational areas, controls, and instrumentation, in order to provide the operators with a vehicle that was safe and simple to operate.

COCKPIT MOCKUP

During the design stage of the vehicle development, a mockup of the vehicle cockpit was fabricated to determine the feasibility of the designer's control and instrumentation arrangement. In addition, the mockup was used to train potential CAV operators.

The study of related research reports and discussions with both designers and operators of other submersibles indicated that the proposed configuration for the vehicle cockpit was inadequate. Sufficient human factors information was not available to either substantiate the actual deficiencies or to redesign the cockpit to provide optimum operator performance. Thus, actual practical experience with a simulated, but realistic, mockup of the operator controls was necessary.

The materials for the mockup were chosen for ease of fabrication and for adaptability on dry land and underwater. The general configuration of the cockpit is shown in Figure 21. Marine plywood was used on most flat surfaces; galvanized sheet metal formed around plywood frames was used to simulate the internal structure of the vehicle cockpit. The mockup was ballasted for submergence by filling the lower pipe skegs with lead.

During dry tests the mockup was generally used inside a shop building. The wet tests were conducted in an open tank, 10 feet deep by 30 feet in diameter. The underwater tests were monitored by closed-circuit television. Video recordings were made of selected portions of the test runs.

Project and human factors engineers, an engineering technician, and two Navy enlisted divers participated in the tests; all the subjects were Navy qualified divers.

Discrete tasks were performed in order that each control and instrument could be checked. The controls were evaluated to determine how well they could be seen, reached, and operated by divers ranging from approximately 5 to 95 percentile in size; the instruments were checked in a similar manner to determine their readability. Following these tests, an evaluation was conducted from a total operational standpoint. Prior to the commencement of the operational tests, each subject was thoroughly indoctrinated as to the function of the control and its relationship to vehicle operation and performance.

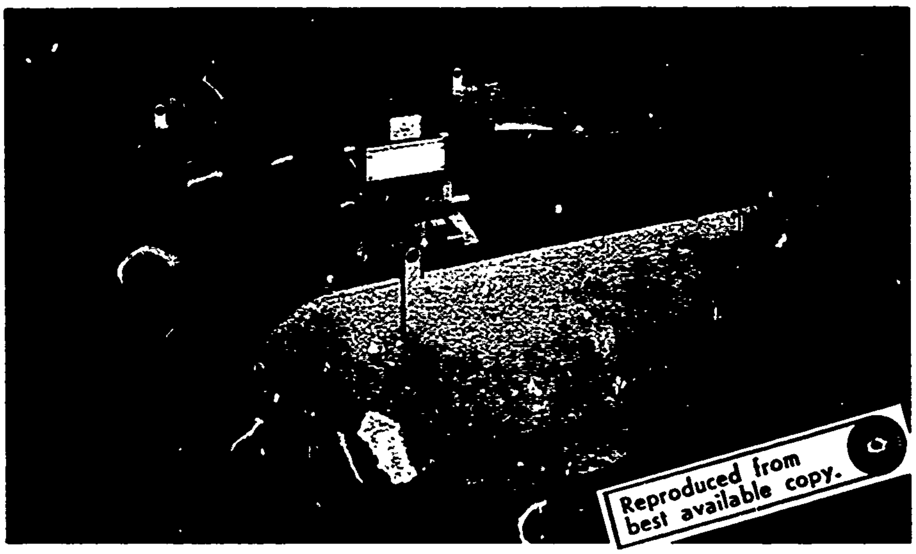


Figure 21. Mockup of cockpit.

Waterproof cards were prepared for transmitting instructions to the vehicle operators; Table 9 lists the operating instructions. The copilot showed one card at a time to the operator, who, in turn, performed the necessary functions. The operator's response was monitored to determine both correctness and ease of operation.

Preliminary tests consisted of evaluating the proposed instrumentation and control arrangement (Figure 22). Initially, it was planned to utilize the pilot and copilot for operation of the vehicle as a dual effort. However, because there was no provision for verbal communication between the operators, it was felt that it would be excessively difficult to operate in this manner. In addition, experienced submersible operators concurred that dual control was an unsatisfactory mode of operation.

Table 9. Operating Instructions

Normal Tasks	Emergency Tasks
1. Turn on power	1. Emergency stop
2. Turn off power	2. Starboard electric motor failed
3. Slow speed ahead	3. Release marker buoy
4. Slow speed astern	4. Large rock 10 feet ahead
5. Full speed ahead	5. Buddy breath
6. Fast starboard turn	6. Your buddy is unconscious
7. Slow starboard turn	7. Make emergency exit
8. Fast port turn	8. Total power failure
9. Slow port turn	9. Cargo shifted forward
10. Normal stop	10. Major air leak
11. Dive using main propulsion	11. Major hydraulic leak
12. Surface using main propulsion	12. Break CAV loose from bottom
13. Blow main ballast	
14. Vent main ballast	
15. Open CAV scuba "K" valve	
16. Breath CAV air	
17. Blow auxiliary ballast	
18. Fill starboard auxiliary ballast	
19. Fill port auxiliary ballast	
20. Fill both auxiliary ballast tanks	
21. Transfer auxiliary ballast from port to starboard	

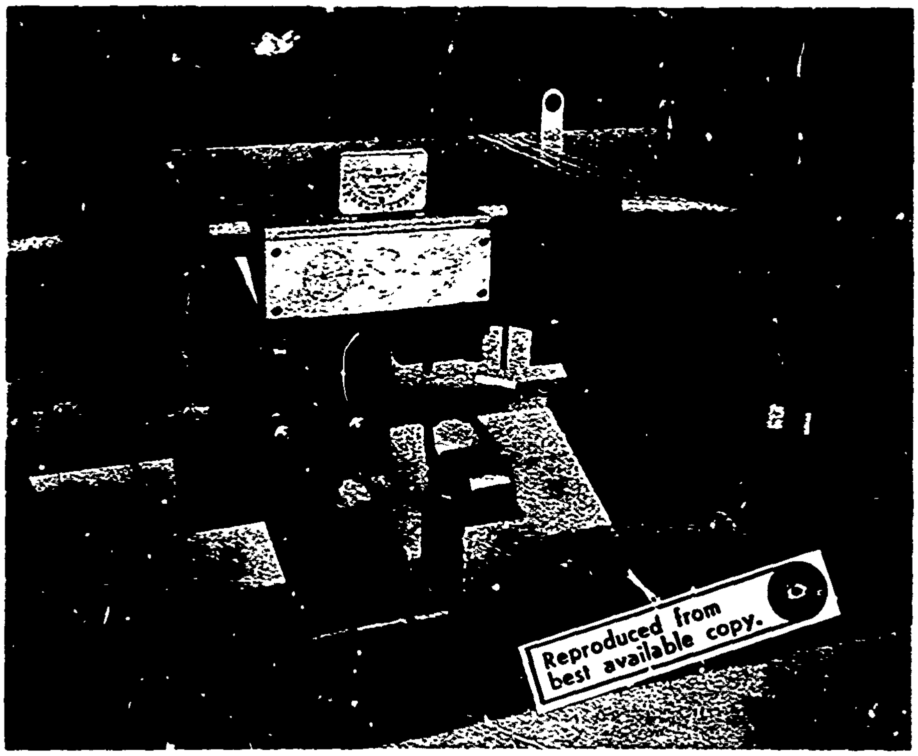


Figure 22. Original layout of instruments and controls.

Using data obtained from the preliminary tests, the vehicle cockpit arrangement was redesigned (Figure 23). This modified cockpit was tested in a manner similar to the original. Table 10 lists the major findings for the preliminary design and for the modified design.

TRAINING

A considerable amount of time was devoted to training divers to operate the CAV. The training program included: (1) classroom instruction on the systems of the vehicle, including predicted operational characteristics and projected methods of control; (2) mockup training with simulated operational commands; (3) tethered wet vehicle familiarization; and (4) shallow water operational tests. An outline of the training program is shown in Table 11.

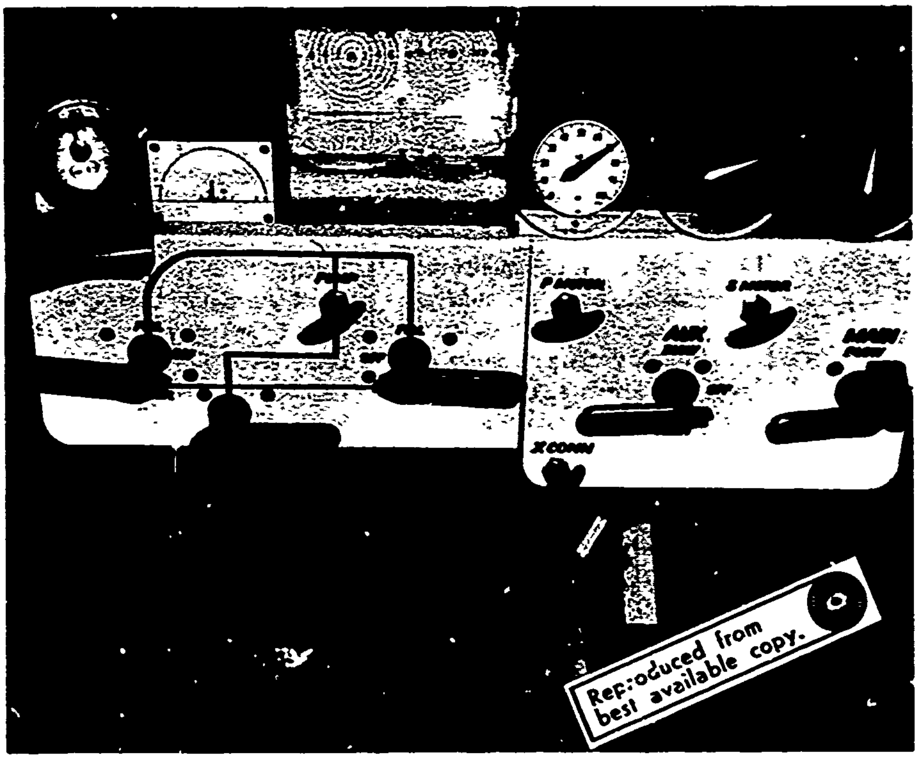


Figure 23. Modified layout of instruments and controls.

Table 10. Test and Evaluation of Original and Modified Mockup

Item	Original Configuration	Modified Configuration
Auxiliary ballast weight gages and air gage	Instrument gage housing excessively large; space needed for controls	Separate housings provided for each gage; gages relocated above controls; gage readability satisfactory; control space obtained
Compass	None provided, but one required	Compass added; position satisfactory
Depth gage	None provided, but one required	Gage added; position satisfactory
Pitch and roll indicators	Separate instruments required for pitch and for roll; pitch indicator very difficult to see in murky water	Instruments integrated into a single combined function unit; configuration and readability satisfactory
Timer	None provided, but one required for diver safety	Conventional stopwatch enclosed in waterproof acrylic housing; readability and reset function satisfactory
Trim weight indicator	Very difficult for operators to see	Indicator was moved from beside to in front of operator; improved display was not provided because of extensive mechanical modification required
Auxiliary ballast control	Accessible but valves req[illegible] o much force to operate r[illegible] difficult for divers to rem[illegible] valve flow logic; pump control was located on Hydraulic Systems Control Panel which was very difficult for operator to see and reach	Ballast control valves relocated below panel face and on flow diagram; valves could be seen and operated satisfactorily; operators could see ballast flow logic on panel; pump control incorporated unifying control functions
Hydraulic control system	Controls very difficult for pilot to see and reach	Controls relocated much closer to the pilot; controls could be seen and operated satisfactorily
Main and auxiliary ballast blow and vent control	Panel too low for operators to see easily; main ballast tanks could be blown accidently	Control panel relocated higher; locking device added to prevent accidental main ballast blow
Main propulsion tilt control	Control can be reached and operated without difficulty but control rotation opposite from rotation of propulsion motors (Figure 16)	Control rotation direction was changed

continued

Table 10. Continued

Item	Original Configuration	Modified Configuration
Scuba K-valve control	K-valve located at pilot's left requiring his regulator hose to pass in front of his body to reach the right side of his regulator; interfered with control operations	K-valve relocated at diver's right rear side; bracket provided for regulator just to the right of his legs; new location and bracket satisfactory
Twin Morse controls	Controls located at diver's right, making operation with both hands difficult (required for fast turns) (Figure 22)	Controls relocated directly in front of pilot; two-hand operation can be accomplished with ease (Figure 15)
Trim weight control	Control position satisfactory	Line added to control wheel to provide improved grip and to readily identify the wheel, as the two control wheels are identical and neither is readily visible to operators
Emergency marker float	None provided, but one is necessary to mark the location of the CAV in the event it is abandoned during ocean trials	A quick-release float added; can be released by pulling pin; further testing required
Hand rails and holds	None provided, but they are required for boarding the CAV when afloat and for aiding fully equipped operators to rise or sit down, especially during wave action	Hand rails and holds added; based on in-tank tests, equipment adequate: sea trials necessary for final evaluation; roll-bar/hand-hold provided to facilitate entry/exit and to protect divers' heads in case of surfacing under vessel
Seats	The seats were not adjustable up and down and were adjustable forward and aft only with difficulty; no back rests provided, but necessary	Fiberglass seats fabricated which provided an easy adjustment in two planes, a back rest, and a tank rest; seats appear satisfactory

Table 11. Training Program for CAV Operator

Meeting No.	Topic	Instruction Time (hr)
1	A. System Functions (a) Electrical systems (b) Hydraulic systems (c) H.P. air system	1-1/2
	B. Conditioning—Harbor Swim	3/4
2	A. System Functions (cont) (a) L.P. air system (b) Main ballast system (c) Mechanical system (d) Auxiliary ballast system	1-1/2
	B. Conditioning—Harbor Swim	3/4
3	A. Basic Performance Characteristics (a) Control functions (b) Instrument functions (c) Speed and trim relationships (d) Stability (righting and trimming movements) (e) Introduction to notebook	1-1/2
	B. Conditioning—Harbor Swim	3/4
4	A. Operating Procedures (a) Pre-dive (b) On surface (c) Diving–surfacing (d) Bottom approaches	1-1/2
	B. Conditioning—Harbor Swim	3/4
5	A. Safety (a) General safety problems (b) Mockup wet test	3/4
	B. Introduction to Math of Trim and Auxiliary Ballast as a Function of Cargo	3/4
	C. Conditioning—Harbor Swim	3/4

continued

Table 11. Continued

Meeting No.	Topic	Instruction Time (hr)
6	A. Notebook Questions and Discussion (a) Physical characteristics (b) Technical aspects (functions and principles)	1-1/2
	B. Conditioning—Harbor Swim	3/4
7	A. Dry Mockup Rehearsal of Basic Vehicle Operational Procedures	1-1/2
	B. Conditioning—Run	3/4
8	A. Dry Mockup Operational Procedure Problems and Critique	1-1/2
	B. Conditioning—Harbor Swim	3/4
9	A. Safety (a) Mouth-to-mouth resuscitation (b) Closed chest heart massage (c) Resuscitator use	1-1/2
10	A. Notebook Questions and Discussion (a) Technical aspects (functions and principles) (b) Operation characteristics (c) Situational procedures	1-1/2
	B. Conditioning—Harbor Swim	3/4
11	A. Safety, Wet Mockup Tests (a) Considerations and procedures (b) Practice (removing injured person from tank)	3/4
	B. Wet Mockup Operational Procedure Problems With Critique	1
12	A. Wet Mockup Operational Procedure Problems With Critique	2

continued

Table 11. Continued

Meeting No.	Topic	Instruction Time (hr)
13	A. Classroom Math Analysis of Trim and Weight Ballast Requirements for Cargo Handling	1-1/2
	B. Conditioning—Harbor Swim	3/4
14	A. Underwater Trim Weight and Ballast Requirement Problems for Cargo Handling	2
15	A. Classroom Load-Handling Procedures (a) Weighing (b) Transporting (c) Lashing	1
	B. CAV Handling From Support Ship	1/2
	C. Conditioning—Harbor Swim	3/4
16	A. In-Tank (wet) Load-Handling Practice (a) Air-bag lift device (b) CAV-type lifting frame (if ready)	2
17	A. Notebook Questions and Discussion (a) Logistics (b) Stability (c) Records	1-1/2
	B. Conditioning—Harbor Swim	3/4
18	A. Classroom CAV Maintenance and Checkout (a) Pre-dive checks (b) Air and battery charging (c) General Maintenance	1-1/2
	B. Conditioning—Run	3/4
19	A. Safety (a) CAV harbor tests (b) CAV at-sea tests	3/4
	B. Briefing for In-Harbor CAV Tests	3/4
	C. Conditioning—Harbor Swim	3/4

Because the CAV is an experimental, one-of-a-kind submersible, only predicted operational characteristics were available during the operator training program. In view of this fact, the actual wet training with the vehicle was conducted under rigid safety considerations. Simplified operations were performed until the operators had gained sufficient confidence. Once the basic procedures for surfacing and submerging became routine, operational tests were conducted.

Prior to commencement of vehicle wet testing, a comprehensive analysis of the vehicle was conducted to determine potentially hazardous conditions. The results of the hazards analysis were implemented in the form of either modifications to eliminate hazards or operational procedures to minimize the danger. Table 12 contains the hazards analysis.

VEHICLE OPERATION

Each vehicle operation was planned in advance, and the operators were instructed in detail as to the requirements of the dive. At the end of the operation, the operators were debriefed to obtain data on vehicle performance and to determine problems with performing the various operations. Modifications were made when it was determined that a particular system or component was not adequate for mission performance.

Prior to the commencement of each diving sequence the vehicle was inspected to insure that all systems were operable and that no potentially hazardous condition existed. In addition, the vehicle life support air and pressure-compensating gas was checked each time the vehicle surfaced.

Table 12. Hazard Analysis of CAV (Wa[illegible]sting)

Area Potential Hazard	Preventive Measures	Emergency Procedures
Electrical systems		
1. Battery explosion because of short circuit and consequent heat buildup	• Check internal wire and connectors (cable attachments in batteries) when battery covers are removed • Check condition of external connectors and cables at regular intervals • Check continuity to ground at regular intervals	• Surface explosion: treat personnel for possible acid burns and general injuries, first-aid kit should contain eye bath; call Base hospital for emergency assistance • Underwater explosion: if personnel injured, divers should surface immediately and be treated as necessary; if no urgency, vehicle should be surfaced using cross-connect function
2. Battery explosion because of hydrogen buildup	• Check operation of relief valves regularly • Open battery vent tubes to check for excess pressure	• Surface explosion. treat personnel for possible acid burns and general injuries, first-aid kit should contain eye bath, call Base hospital for emergency assistance • Underwater explosion: if personnel injured, divers should surface immediately and be treated as necessary: if no urgency, vehicle should be surfaced using cross-connect function
3. Rupture of battery cases because pressure compensation system failed	• Check batteries and make sure bladders full of oil prior to each diving operation	• If on surface, abort mission • If underwater, surface using cross-connect function
4. Cable connections not fully mated and accidentally disconnected	• Make sure cables fully mated and dummy plugs in place prior to each dive	• If on surface, abort mission • If underwater, surface using cross-connect function
5. Shock hazard to divers during underwater tests	• Check continuity to ground at regular intervals • Check condition of external connectors and cables at regular intervals	• If in water, turn off electric motors; surface divers, treat injured personnel as necessary
6. Excessive heat buildup in motor and pump canisters	• Run motors on surface to check for heat buildup	• Use cross-connect function to surface vehicle
7. Ruptured or crushed motor canisters because pressure compensation system failed	• Check compensation system prior to each dive	• Shut motor down and use cross-connect to surface vehicle

continued

Table 12. Continued

Area Potential Hazard	Preventive Measures	Emergency Procedures
Propulsion systems		
1. Diver or deck personnel injured by rotating propellers	• Notify all personnel to stay clear of propulsion systems	• Treat injured personnel as necessary
2. Damaged propeller	• Make sure propellers are undamaged and unobstructed before diving • Check for free rotation	• Surface using auxiliary propulsion
Hull structures		
1. Possible injury to operators because of unsecured equipment or lines or sharp edges on structures	• Make sure all lines and equipment are secured • Check all hull structures for jagged or sharp edges	• Treat injured personnel as necessary
2. Possible CAV operational failure because of damage to hull tubes or other structures	• Check all welded seams prior to off-loading • Check for leakage of air from hull structure immediately after submerging	• Abort mission in the event of damage
Hydraulic systems		
1. Hydraulic lines rupture or motor oil seals leak causing loss of hydraulic oil and possible failure of hydraulic systems	• Inspect all hydraulic equipment and lines for leaks or damage • When submerged, watch water for indication of hydraulic oil leaks	• Abort mission in the event of damage
2. Failure of hydraulic pump or motor	• Check operation prior to each dive	• Abort mission in the event of damage
High pressure air system		
1. Operators injured as a result of a high pressure line whipping following rupture or failure of the fitting	• Frequently check all high pressure lines for damage and make sure secured • Prior to use check charging line for damage and make sure tied down at both ends	• Treat injured personnel as necessary • Abort mission in the event of damage

continued

Table 12. Continued

Area Potential Hazard	Preventive Measures	Emergency Procedures
High pressure air system (cont)	• After off-loading the CAV check for excessive air leaks • Check tanks, valves, and fittings for damage or corrosion	
2. Failure of system	• Check high pressure air system prior to dive	• Divers should breathe from personal scuba tanks • Treat injured personnel as necessary • Abort mission in the event of damage • Divers should abandon CAV on bottom and surface
Low pressure air systems 1. Divers' air supply inadequate during main ballast blow	• Check this function under safe conditions	• If unsafe, diver should breathe from personal scuba tanks
2. Low pressure air leaks into main ballast tanks underwater resulting in CAV instability or an unplanned ascent	• Make sure main ballast blow valve is always in vent position except during actual blow function	• Abandon vehicle if deemed necessary
3. Failure of system	• Check main and auxiliary ballast blow before descending	• Divers should abandon CAV on bottom and surface
Life support system 1. Divers become incapacitated to some degree because of contaminated air	• Check air purity by analysis at regular intervals	• Divers should breathe from personal scuba air and surface CAV
2. Regulators or hoses malfunction, necessitating emergency use of backpack scuba air	• Check regulator function prior to each dive • Use proper preventive maintenance • Check hoses for damage	• Divers should breathe from personal scuba air and surface CAV

continued

Table 12. Continued

Area Potential Hazard	Preventive Measures	Emergency Procedures
Stability systems		
1. Excessive roll or pitch because of surface conditions, resulting in possible injury to operators	• Do not operate in sea state over 2	• Abort mission; secure CAV to emergency buoy or leave on bottom as required
2. Trim weights jam forward or aft because of broken or tangled cables or foreign material in tubes	• Check cables at regular intervals for excessive wear • Check trim weights position prior to each dive	• Attempt to correct vehicle trim using auxiliary ballast tanks; if vehicle becomes excessively unstable, abandon CAV immediately
3. Auxiliary ballast system fails because tanks flood from structural damage or ruptured water or air lines	• Inspect piping and hull structure for damage	• Attempt to correct using trim weights; if vehicle becomes excessively unstable, abandon immediately
4. Ascent rate becomes uncontrolled or excessive because auxiliary or main ballast tanks accidentally blown	• Always make sure the main ballast control valve is in VENT position and auxiliary ballast control valve is in OFF position while underwater	• Attempt to correct with trim weights or by altering valve position; abandon CAV if ascent rate becomes excessive
5. Shifting of cargo	• Make sure all cargo securely fastened	• Attempt to correct with trim weights or by altering valve position; abandon CAV if ascent rate becomes excessive
6. Descent rate excessive because of excess negative buoyancy	• Insure vehicle is neutrally buoyant before diving	• Tilt propulsion motors up and surface; if uncorrectable, abandon vehicle
Handling		
1. Personnel injured by CAV falling during crane-handling operation	• Only riggers allowed near CAV during handling operations • No diver permitted in water during on- or off-loading • Check lifting eyes and cables before each operation	• Use emergency first-aid procedures as necessary

continued

Table 12. Continued

Area Potential Hazard	Preventive Measures	Emergency Procedures
Handling (cont)		
2. Excessive swing on end of crane cable because of adverse sea conditions	• Avoid operating under such conditions • Use tie lines for dampening swing if possible	• Tie CAV to mooring buoy if necessary • If swing becomes excessive, lower CAV into the water and tie it to mooring buoy
3. Surface collision of CAV	• Avoid operating in excessive sea states • Do not allow divers in water when coming alongside any structure • Use tag lines from support vessel when sea state permits	• If CAV is sinking, abandon immediately
4. Diver becomes entangled in handling or lift line	• Have operators stay clear of handling line area while vehicle underwater • Use shock cord betwe[illegible] the legs of the lift bridle	• If operator injured, use emergency first-aid procedures, and slack lines if necessary
Other operational hazards		
1. Underwater collision	• Survey area to make sure there are no large obstructions and that visibility is satisfactory • Notify mariners; ke[illegible]ll boats out of area	• If vehicle is not excessively damaged, surface and check CAV for damage; abandon CAV if necessary • Use emergency first-aid procedures if necessary
2. Visibility reduces below permissible limits while submerged	• Abort missi[illegible]ecomes excessive or visibility limited	• If conditions permit, surface; if not, abandon CAV on bottom
3. CAV strays off course or survey is inaccurate and depth becomes excessive during dive	• Monitor CAV depth gage to detect such a condition developing	• Surface if possible; if not, abandon CAV
4. CAV surfaces under support vessel or any other structure	• Make sure operating area is clear of support craft • Use a work boat to follow divers exhaust air bubbles and warn other craft to stay clear of area if possible	• If CAV comes up under warping barge or other structure, submerge, if possible, maneuver to clear area, and surface

continued

Table 12. Continued

Area Potential Hazard	Preventive Measures	Emergency Procedures
Other operational hazards (cont)	• Instruct operators to observe air–water interface • Install roll bar on CAV	• Abandon CAV, and treat injured personnel if necessary
5. CAV becomes entangled in kelp or lines	• Select operating site carefully	• Operators should clear CAV if possible